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**AFWAL-TR-80-3120
Volume III**



FORCE MANAGEMENT METHODS TASK II

**Volume III Attack/Fighter/Trainer
Aircraft Evaluation of
Potential Improved Methods**

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November 1980

TECHNICAL REPORT AFWAL-TR-80-3120, Volume III

Interim Report for Period October 1978 to July 1980

Approved for public release; distribution unlimited

**FLIGHT DYNAMICS LABORATORY
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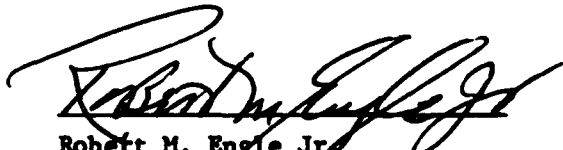
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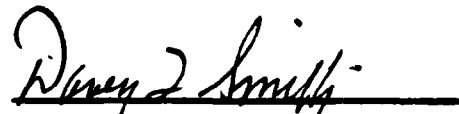
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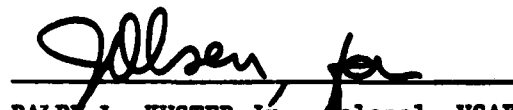
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-80-3120, Vol. III	2. GOVT ACCESSION NO. AD-A11 8860	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FORCE MANAGEMENT METHODS TASK II - Volume III. Attack/Fighter/Trainer Aircraft - Evaluation of Potential Improved Methods.		5. TYPE OF REPORT & PERIOD COVERED Interim Report Oct 78 - Jul 80
7. AUTHOR C. E. Larson and D. J. White		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Vought Corporation P. O. Box 225907 Dallas, TX 75265		8. CONTRACT OR GRANT NUMBER(s) F33615-77-C-3122
11. CONTROLLING OFFICE NAME AND ADDRESS Flight Dynamics Laboratory (AFWAL/FIBE) Air Force Wright Aeronautical Laboratories Wright Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Proj 2401-01-19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE November 1980
		13. NUMBER OF PAGES 146
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; Distribution Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Vought is a Subcontractor to the University of Dayton Research Institute		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Force Management, structures, flight loads, structural life management, fatigue, structural integrity, structural maintenance, inspection scheduling, data recording, data analysis, damage tolerance, individual aircraft tracking.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents an evaluation of candidates for potentially improving Force Management methods for attack/fighter/trainer aircraft. These potential methodologies have been ranked and graded according to cost, accuracy, ease of implementation and overall effectiveness.		

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FOREWORD

The Vought Corporation, under a sub-contract to the University of Dayton Research Institute (UDRI), has conducted a study of attack/fighter/trainer aircraft Force Management Methods. The Air Force contract number is F33615-77-C-3122, and the contract instrument between UDRI and Vought is Purchase Order RI 82707. The program is sponsored by the Air Force Flight Dynamics Laboratory Structural Integrity Branch (AFFDL/FBE). Captain Adrian Robbe, USAF, is the Air Force Project Engineer. The contract program Managers are Dr. Alan Berens of UDRI and Charles E. Larson of Vought.

Task I of the referenced contract resulted in a report (AFFDL-TR-78-183) which outlined current practices and methods used by the Air Force. This report is the product of the Task II effort and addresses improved force management methods for attack/fighter/trainer aircraft. The final product of the program will be a Force Management Handbook to be compiled from the above mentioned interim reports.



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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the Force Management (FM) Task I effort was to survey the present methods, procedures, and practices being used by the Air Force (and its contractors) in pursuit of the assurance of the structural integrity of its airplanes. The purpose of this Task II effort was to evaluate, grade, improve, or otherwise contribute to the enhanced efficiency of Air Force FM methods.

The investigators of the Task II study were also charged with hypothesizing new methods where applicable. These hypothesized, improved methods were to consider the best features of any present method or combination of methods while applying the latest technology available in the fields of electronics and instrumentation.

This report is organized with the format of a Force Management Handbook (the final deliverable item to the Air Force) in mind. Since the Handbook will include data from both Task I and Task II, the sections appearing here are organized to be compatible with the anticipated format of the Handbook.

1.2 SCOPE

This volume of the Task II effort is concerned with the elements of FM as they apply to attack/fighter/trainer airplanes. The topics or elements addressed here are individual aircraft tracking (IAT) methodology, loads/environment spectra survey (L/ESS) methodology, force structural maintenance planning (FSMP) and the coordination of these three. The emphasis was distributed among these four topics according to the following proportion: IAT, 63%; L/ESS, 20%, FSM, 10%; and coordinated FM, 7%. Additional resources were available to be expended on report preparation, conferences, and handbook support.

In summary, the Task II effort has ranked and graded the IAT and L/ESS methodologies according to cost, accuracy, ease of implementation, and overall

effectiveness. New methods have been hypothesized that combine the best features of present methods and present technology. The FSMP function has been addressed in an evaluative manner and recommendations are made for improvements in the coordination and interfaces of the FM elements. Auxiliary data has been included in the Appendices. Appendix A reports a study concerned with use of counting accelerometer data in damage index algorithms. Appendix B is a study comparing the counting accelerometer and mechanical strain recorder accuracies for the IAT function. This appendix also discusses the problem of damage transfer. Appendix C summarizes results from an MSR program on the A-7D airplane. This program provides information pertinent to use of the MSR for either IAT or L/ESS activities.

2.0 BACKGROUND

Maintaining the strength, rigidity, damage tolerance, and durability of USAF aircraft structures is dependent on the capability of the appropriate Air Force commands to perform specific inspection, maintenance, and possibly modification or replacement tasks at specific intervals throughout the service life (i.e., at specific depot or base levels maintenance times and special inspection periods). To properly perform these tasks, the Air Force must have detailed knowledge of the required actions. Additionally, experience has shown that the actual usage of military airplanes may differ significantly from the usage assumed during design. Likewise, individual aircraft within a fleet may experience a widely varied pattern of usage severity as compared to the average aircraft. Continual adjustments to initially determined safe crack growth intervals must be made for individual aircraft to ensure safety and to allow for modification and repair on a timely and economical basis. It is necessary, therefore, that the Air Force have the technical methods and actual data to assess the effect of these changes in usage on airplane damage tolerance and durability.

Force Management is the responsibility of the Air Force and is accomplished in accordance with the Force Management Tasks of MIL-STD-1530A (Ref.1) using a data package provided by the contractor for each new airplane system. While it is recognized that specific force management methods will be selected to fit the needs of each specific aircraft system, it is anticipated that guidelines, procedures, and requirements can be defined which have general applicability to each of the major aircraft classes.

The objective of this program is to develop the force management methods, procedures, and techniques necessary to ensure the damage tolerance and durability of individual aircraft during force operations. These methods shall provide the capability to develop baseline operational spectra, predict

potential flaw growth based on individual aircraft usage, and plan structural maintenance actions. The methods to be developed under this program will have general applicability to each of the major aircraft classes (fighter, transport, bomber, etc.). The results of this program will be used to develop guidelines for accomplishing the Force Management Tasks of MIL-STD-1530A. A force management handbook will be developed which will contain these methods and guidelines.

Contractors developing a new aircraft are required by Air Force Regulation 80-13 to comply with MIL-STD-1530A in providing the Air Force with a force management data package. This data package consists of the necessary data acquisition and reduction techniques and analysis methods to acquire, evaluate, and utilize operational usage data to provide a continual update of in-service structural integrity. It is the responsibility of the Air Force to utilize the force management data package to provide quantitative information for decisions regarding force structure planning, modification priorities, and related operational and support decisions. Under Air Force Regulation 80-13, each of the participating commands (AFSC, AFLC, and operating commands) is assigned specific responsibilities in accomplishing the Force Management Tasks of MIL-STD-1530A. AFSC responsibilities include the development of advanced data acquisition, reduction, and analysis techniques for structural data collection programs. The structural data collection and analysis efforts are the responsibility of AFLC. AFLC also has responsibility for scheduling and accomplishing force structural maintenance actions. Operating command responsibilities include operation and maintenance of recording system hardware and acquisition of operational usage data.

Three basic elements of the force management data package are the Force Structural Maintenance (FSM) plan, the Loads/Environment Spectra Survey (L/ESS), and the Individual Aircraft Tracking (IAT) program.

The FSM plan identifies inspection and modification requirements, including criteria, schedules, and detailed procedures for use at field or depot level. Complete detailed information (when, where, how, and cost data, as appropriate) is included in the plan. The FSM plan is used by the Air Force to establish budgetary planning, force structure planning, and maintenance planning. The initial version of the FSM plan is based on design service life, design usage spectra, and design analyses revised to include the results of design development and full scale tests. After the aircraft is in service, the initial FSM plan is updated to include the baseline operational spectra developed from the L/ESS.

The objective of the L/ESS is to define actual stress spectra for critical areas of the airframe based on operational usage. A portion (10% to 20%) of operational aircraft is instrumented to measure such parameters as velocity, acceleration, altitude, fuel usage, temperature, strains, etc. This data is then used to construct the baseline operational spectra. Normally, the duration of the L/ESS is three years or when the total recorded flight hours of unrestricted operational usage equals one design lifetime, whichever occurs first.

The objective of the IAT program is to predict potential flaw growth in critical areas of each airframe based on individual aircraft usage data. A tracking analysis method is developed to establish and adjust inspection and repair intervals for each critical structural location of the airframe. This analysis provides the capability to predict crack growth rates, time to reach crack size limits, and crack length as a function of total flight time and usage data. A data acquisition system is developed which is as simple as possible and is the minimum required to monitor those parameters necessary to support the tracking analysis method. The IAT program provides data to derive individual maintenance (inspection and repair) times for each aircraft.

With the updated FSM plan and the individual aircraft maintenance time

requirements available, the Air Force can determine adjusted times at which the force structural maintenance actions, as specified in the FSM plan, must be performed on individual airplanes and each critical area thereof. The Air Force can then schedule force structural maintenance actions on a selective basis that accounts for the effect of usage variations on structural maintenance intervals.

The goal of this program was to develop the force management methods, procedures, and techniques necessary to ensure the damage tolerance and durability of individual aircraft during force operations and to develop guidelines for accomplishing the Force Management Task of MIL-STD-1530A. These methods and guidelines will be incorporated into a force management handbook for use by the Air Force and airframe contractors in complying with the Force Management Task of MIL-STD-1530A.

3.0 FORCE MANAGEMENT ORGANIZATIONS

This section discusses recommended interfaces between the major parties involved in the FM, IAT and L/ESS efforts. The discussion is divided into two cases: before the transfer of responsibility for an airplane model's structural integrity from the ASD/SPO cognizance to that of the AFLC and after the transfer of this responsibility. These cases are schematically represented by Figure 3-1 and 3-2, respectively.

The "ASIMIS" mentioned in these charts is not the ASIMIS that exists today. The organization envisioned here has an expanded charter with areas of responsibility that not only include the present support oriented computer services but also new areas of policy and decision making. The present ASIMIS carries a name that strongly suggests the existence of this expanded responsibility: Aircraft Structural Integrity Management Information Systems. A slightly improved name for the hypothetical new organization could be ASIIS, Aircraft Structural Integrity Information Systems. The words "Structural Integrity Management..." would be missing and there could be no confusion to the effect that the actual structural management function would be done by any other than the structural manager. The designation "ASIMIS" is used in the subsequent discussions to avoid the impression that a new organization must be created to solve a problem or improve efficiency.

Of the four principal organizations presently involved in ASIP (the SPO/structural manager, the contractor, and ASIMIS) for an airplane, the only one that is involved before and after the transfer of responsibility is ASIMIS. The concept recommended here suggest that ASIMIS (or some alternate organization with the prescribed duties and authority) be staffed with data acquisition system technology expertise as it relates to the ASIP function. No one such organization with these characteristics is known to exist within the Air Force. The duties described for the new hypothetical ASIMIS are now performed variously by the present ASIMIS and Headquarters, AFLC personnel.

Other duties are performed by contractors and SPO staffs. The continuity achieved by the active participation (in a FM data sense) of one single organization during the development of one airplane after another would make a great contribution to the efficiency of FM data systems selection and application. The ASIMIS would constitute a unique experience base for FM-peculiar data problems.

First it is recommended that control of the airplane's ASIP responsibilities be roughly separated by the duration of the L/ESS program: during the L/ESS the SPO and contractor will have responsibility; after the three year period, the transfer is made to the Logistics Command. During the L/ESS program it is recommended that all the IAT and L/ESS data be sent to an organization such as ASIMIS for screening, processing, gap-filling, reduction, and display. This recommendation is subject to variations. That is, a particular airplane may have needs that demand the contractor's participation in the early L/ESS data activity. The basic idea here is for the ASIMIS to at least be near for education and coordination.

It is further assumed that the airframe contractor will have supplied the data processing tools and methodology to ASIMIS. If this has not been done, then the contractor will act in a support role until this objective has been accomplished. It is concluded that the ASIMIS should be established as the best qualified and designated as the data processing agent for the Air Force for every airplane model. To adequately perform these duties, it is imperative that ASIMIS be involved at the earliest point in the data activity. The ASIMIS' advice and consent would be sought with respect to the development of the processing tools and methodology decisions. Decisions on equipment selection, parameter selection, and data processing scope should be approved by ASIMIS. Such involvement seems only to enhance the probability of a smooth operation when the contractor is no longer involved. It is possible,

or even likely, that the contractor will perform the bulk of the effort associated with L/ESS operation. However, this should be allowed only with the concurrence of ASIMIS acting as the responsible organization. ASIMIS must be heavily involved with L/ESS in the event that a secondary program is initiated later in the life of the airplane. If ASIMIS is given the stature as the near-exclusive ASIP data acquisition, reduction and planning agency for the Air Force, centralized responsibility for all data activities will be realized.

The ASIMIS will furnish the reduced data to the office of primary responsibility (OPR), assumed to be the SPO at this stage, for technical use. The contractor and future structural manager both will be in an advice and consent capacity during this data monitoring/accumulation phase. It is anticipated that there will be little or no instructions for special maintenance actions until well into the three year L/ESS period. The instructions to the using commands will initiate with the SPO along with the FM update activities. The data monitoring phase will result in any refinements to the IAT program and FSM plan.

It is again recommended that the ASIMIS retain and possibly extend the capabilities of any and all computer processing tools associated with L/ESS. After exposure to the L/ESS experiences of several airplanes, it is judged that ASIMIS would be able to assume more and more responsibility for future programs. It is believed that overall the FM functions can be achieved at a lower cost when performed internally in the Air Force. No organization is in a better position to know and understand the structural requirements of an airplane better than the contractor. However, a highly experienced Air Force ASIP data group, used in conjunction with the contractor stated needs, will result in more cost effective data systems.

After the L/ESS program is completed, the IAT data alone will flow to

the ASIMIS. The structural management is transferred to an Air Logistics Center, or equivalent. The ALC will receive the IAT data from ASIMIS and will have primary responsibility for executing the maintenance program. The contractor and the SPO will be available to support this responsibility. A well designed and executed IAT and L/ESS will result in a smooth transition of this responsibility and the subsequent structural management of an airframe.

If the ASIMIS were to be properly commissioned as the Air Force data agency, some authority would be given to hold the user commands accountable for loss of data, primarily during the L/ESS program. As will be discussed later, a major change in attitude on the part of the users is mandatory if the Air Force is to realize a reasonable return on investment of L/ESS resources. The breakdown in the data acquisition system is now one of the larger FM problems. This system's performance is not commensurate with the quality and intent of the ASIP/FM/MIL-STD-1530A concept.

It is suggested that the above described FM organizations interfaces would provide substantially more streamlined, systematic, and efficient data flow. An important feature, now missing to some extent, is accountability. ASIMIS would have the responsibility for the selection and performance of the FM data systems and it would have to be satisfied before funds were allocated for any new data acquisition system. ASIMIS would soon develop an educated position on the needs of any new airplane requirements.

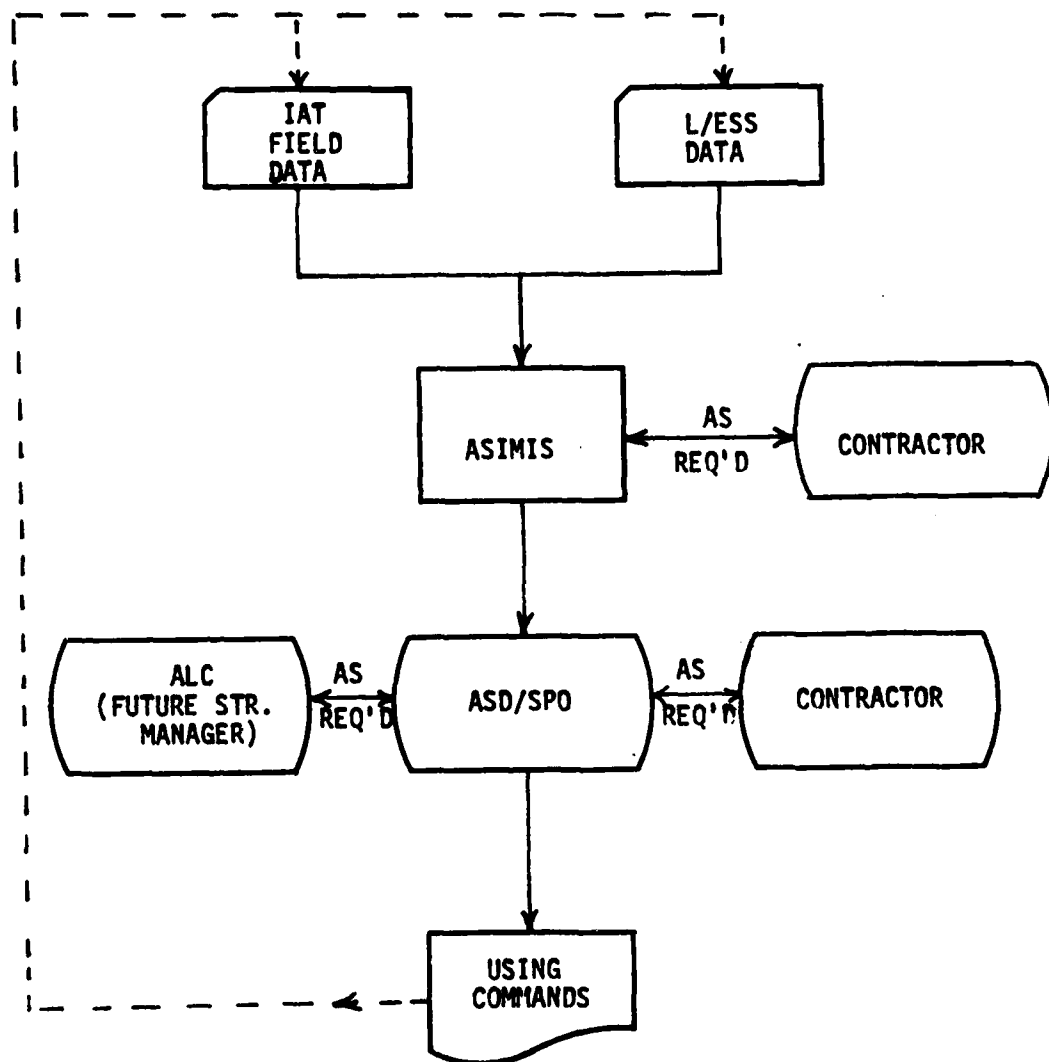


FIGURE 3-1. RECOMMENDED FM DATA FLOW BEFORE TRANSFER OF ASIP RESPONSIBILITY

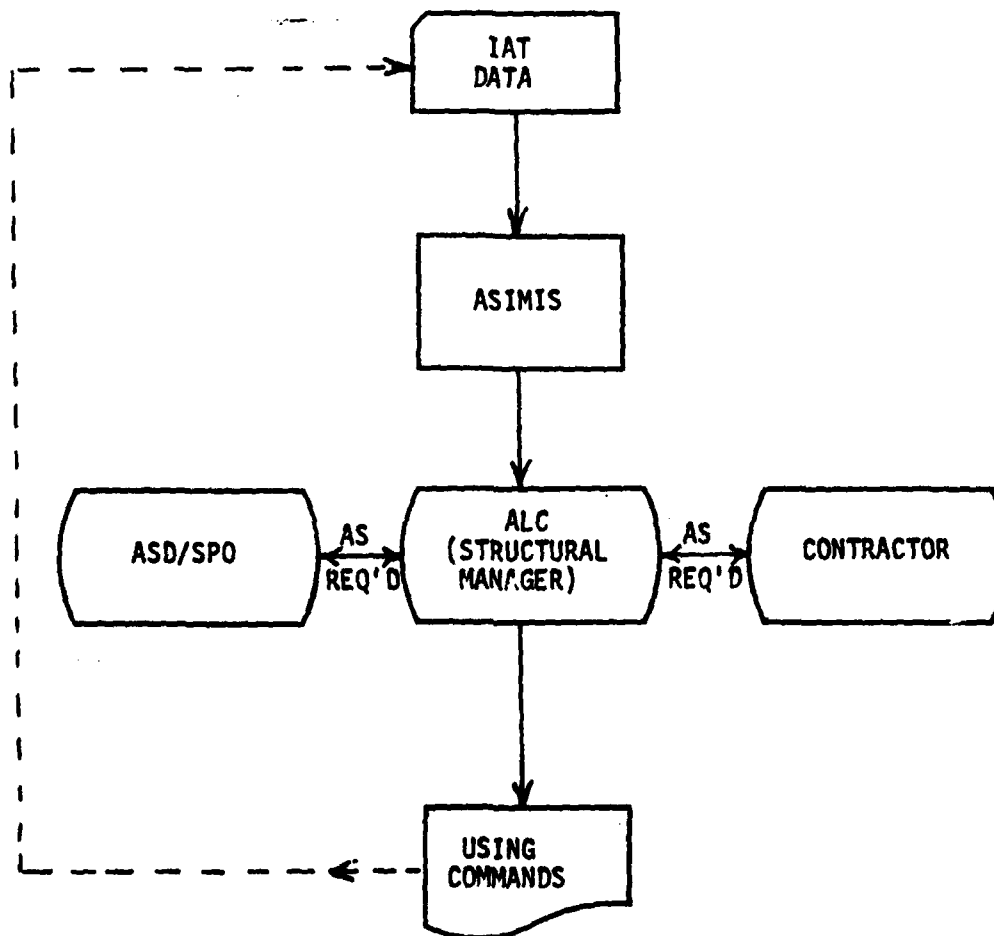


FIGURE 3-2. RECOMMENDED FM DATA FLOW AFTER TRANSFER OF ASIP RESPONSIBILITY

4.0 GUIDELINES TO FM METHODS

A discussion on guidelines for the selection of FM/ASIP methods must be centered about two considerations of paramount importance: (1) to provide for the absolute minimum information required to satisfy the need, and (2) to acquire and use the data. The declaration of these considerations seems redundant and superfluous. However, the state-of-the-art survey performed under Task I of this FM investigative effort discusses several cases (in the recent past) in which neither of these considerations were noted.

Over-reactions to the intent and requirements of the FM function may result in expensive and extraordinarily inefficient data systems and methods. These instances will occur when the engineering and technical community is allowed too much influence in the design and scope of the ASIP data management system. The tendency is to ask for more data than is necessary to accomplish the FM task. This is highly inefficient and uneconomical. In short, the FM effort should be subjected to the same design to cost philosophy as other elements of the airplane program.

It is believed that with the existence of an organization such as an extended ASIMIS as described in Section 3, this is less likely to happen. An organization with continuity of experience will necessarily learn what is a reasonable amount of data required to do an adequate job. Guidelines for the L/ESS and IAT functions are given below.

4.1 L/ESS GUIDELINES

Paragraph 5.4.4 of MIL-STD-1530A states that

- (1) the objective of the L/ESS program is " ... to define the actual stress spectra for the critical areas of the airframe,"
- (2) the duration of the L/ESS program is assumed to be the lesser of three years or when one design lifetime is reached,
- (3) a separate L/ESS program may not be required if an adequate IAT program is available.

It is concluded in the Task I report that unnecessary parameters were selected for incorporation in past L/ESS program as a hedge against unforeseen structural problems. This is attributed to the timing of the selection requirements by the Air Force. That is, selections were made before a complete critical area identification analysis was ended. The L/ESS program cannot be scoped to accommodate an arbitrary, unanticipated operational problem. For this reason the timing requirements on the selection of parameters must be eased to allow benefit of complete analysis and test. Another relieving element is the advent of MIL-STD-1553B which provides for future airplane weapons systems to have a data bus capability. This is a method which provides an information capability containing all the airplane response and control parameters used by the pilot or air data computer. This bus will provide very useful L/ESS resource data (for needs other than special strain gages, etc.)

The recommended guideline for L/ESS is that special unanticipated structural problems be treated with ad hoc data acquisition programs. The final design of the L/ESS program should be completed at the last possible moment and should not be burdened with any duties other than establishing the operational stress spectra of predicted critical areas.

The suggestion by MIL-STD-1530A concerning the three year duration for L/ESS is also widely ignored. A recommended guideline for the design of a L/ESS program is that it be organized to accomplish its stated objective within the three years. The statement of item (3) above concerning the possible coupling of the IAT and L/ESS programs has the greatest potential for FM program efficiency for at least some airplanes. Such an optimization and coupling of the IAT and L/ESS functions is a natural product of the knowledge obtained from several iterations by the "ASIMIS" organization of Section 3.

The final L/ESS guideline topic to be discussed here is the wisdom of

attempting to acquire data for use in future airplane design efforts. The interpretation is widely made that the acquisition of this type of data (airplane response parameter) is an objective of L/ESS. This requirement is not stated in paragraph 5.4.4. It is possible that this type of data could be serendipitous to a L/ESS program, but obtaining this data is expensive and is not required under the MIL-STD-1530A definition of the L/ESS program. There is controversy about the usefulness of such data for future design in an environment of widely spaced model procurements and fast changing technology.

4.2 IAT GUIDELINES

The primary guideline for the IAT function is to select a tracking variable set that produces an optimization of accuracy, cost, and complexity. One additional demand on the IAT is that of continuity or correlation or interface with the L/ESS program. For example, if a counting accelerometer (CA) system is to be selected as the IAT variable, the vertical acceleration must be included in the L/ESS list of variables. The data collected from the two sources should be correlated so that the IAT program may in effect be a mini-L/ESS at the expiration of the normal L/ESS.

Essentially the present choices of (non forms) IAT variables are reduced to two: the CA and strain counters. The CA is graded as a good compromise choice in Section 6; however, the strain counter method if used in conjunction with electronics is graded first. The fact is that the IAT function is the best performer of all the elements of IAT and it is difficult to make a gross error in this choice when selecting from current methods.

5.0 FORCE STRUCTURAL MAINTENANCE PLAN

The objective of a Force Structural Maintenance Plan (FSMP) is to identify the airplane force inspection and modification requirements that pertain to the structural integrity of the airplanes. These requirements may address the airframe as a unit or as individual major components such as the wing or fuselage. The component coverage may be a requirement for cases where parts are interchanged between airplanes during maintenance or overhaul. The principles involved in tracking complete airframes and major components are similar; the bookkeeping requirements are simply more extensive when components are accommodated.

The FSM requirements are a natural product of the ASIP tasks performed on an airplane under the guidance of MIL-STD-1530A. These analyses and tests will reveal anticipated problem areas and accompanying solutions or treatments. These requirements theoretically are identified in sufficient detail to allow the OPR to establish force budgetary planning, structural integrity planning, and maintenance planning. The FSMP, as prepared by the airframe contractor, is initially based on design information and later supplemented by results of the L/ESS program.

The FSMP fits into the overall concept according to Figure 5-1. The original design analyses and test define the limitations of the airframe relative to accomplishing the assumed missions and life. The required inspections and maintenance treatments are then tentatively programmed. The periodic results of the IAT program will furnish the structural manager the checkpoints for executing the scheduled maintenance action. Concurrent with this activity is the L/ESS program which updates mission usages and the impact of mission changes on the structural integrity of the airframe. New maintenance action schedules are created to conform with the operational realities of the force. The updated FSMP is continually keyed to the IAT data. This overall approach to FM is theoretically very effective. Certain

ELEMENTS OF USAF FORCE MANAGEMENT

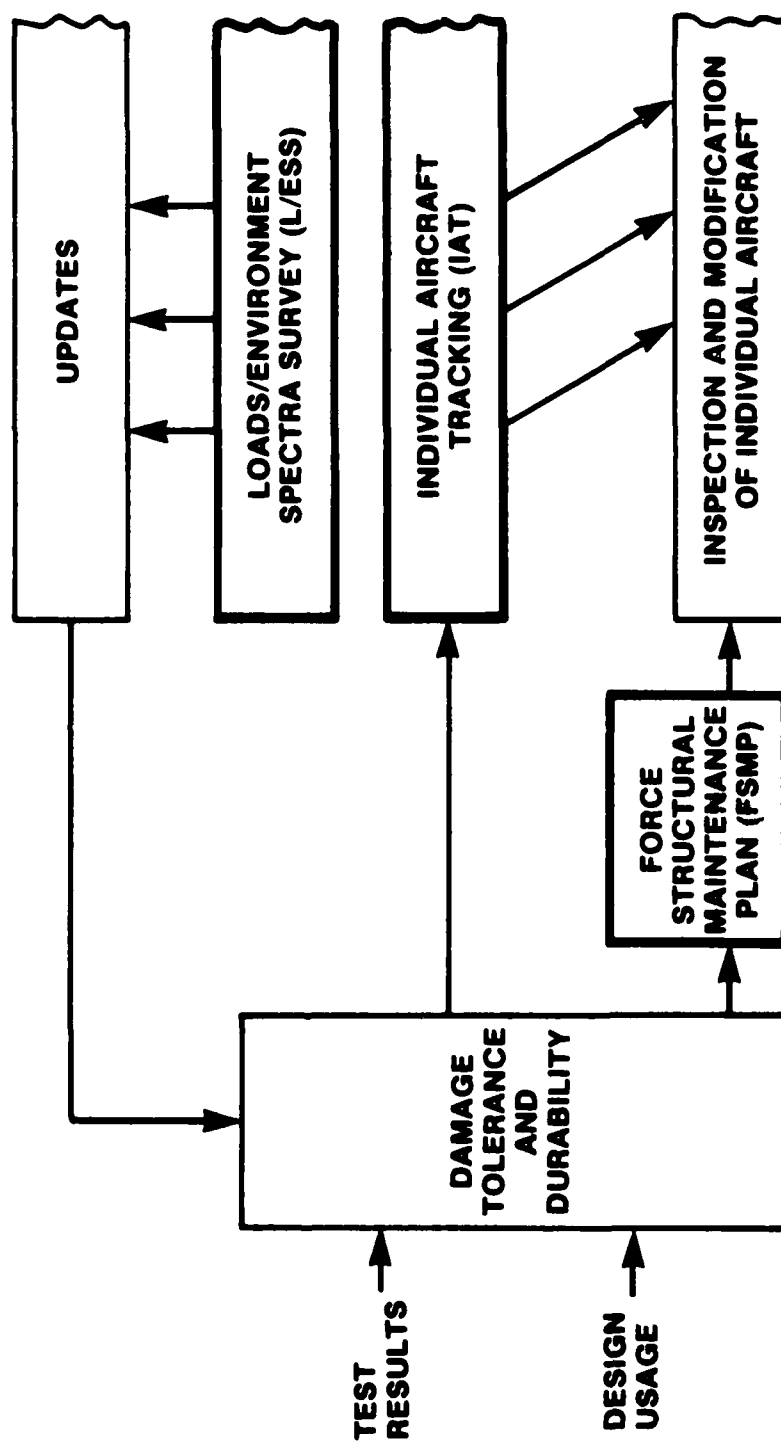


FIGURE 5-1

improvements in areas such as timing are apparent and will be discussed below.

5.1 STRUCTURAL MAINTENANCE ACTION DETERMINATION

Aside from the "routine" airframe maintenance actions such as corrosion inspections and treatment, hard landing inspections, alignment checks, etc., all the structural integrity inspections may be driven by the damage index as reported by the IAT program. The objective of the FSMP is to provide the Air Force with the necessary information and instructions to execute a complete structural maintenance program.

Since there has been only one airplane (the F-16) procured by the Air Force under MIL-STD-1530A and its FSMP is not yet published, there is no basis for making recommendations or improvements to FSM procedures. However, an interpretation of the requirements of the Standard in terms of the FSMP will be given. The FSMP document should contain the following principal data groups.

- (1) A delineation of all anticipated inspection, repair, and modification activity proposed for the airplane. This information should be time phased by sequential airplane identities. Resource requirement estimates should be given for the benefit of the Air Force long range planning activity.
- (2) A summary of the critical location and the damage index values that key the required maintenance actions.
- (3) Supporting data required for a full explanation of procedures to be incorporated into the Air Force T.O. system.

The information contained in item (2) above represents the essence of the FSMP. Figure 5-2 is a compilation of the type of data required. Figure 5-3 is an example of a display format for this data. These figures are official charts for the A-7D that will, in effect, be a part of its FSMP. When the structural manager has a document containing this detailed information available to him, the structural management effort reduces to that of issuing messages to the operational commands announcing the airplanes to be acted on.

OPERATIONAL LIMIT AND INSPECTION PERIOD SUMMARY-EQUIVALENT B.L. SPECTRUM FLIGHT HOURS

	Item	Economic Limit (Hrs) 0.005 → 0.03	Inspection Interval (Hrs) 0.05 → a_p/DI	Safety Limit (Hrs) 0.05 → a_c/DI	Special Considerations
1	MCS Skin at Inbd, Outbd. Pylon Post Aft (No. 3 and 7)	> 8,000	<u>2,100</u> / .28	2,200/.55	
2	Fuse Blkhd 480 Lug d=1.5 (No. 55) d=1.75	> 8,000	<u>2,150</u> / .28 <u>2,550</u> / .39 <u>4,000</u> / 1.00	2,300/.58 3,100/.78 8,000/2.00	Apl's → 391 Apl's 392 & 393 a1 = .022
3	MCS Wing Attach Rib Yw=24.6 (No. 14)	3,800	<u>2,500</u> / .63	5,000/1.25	
4	MCS Wing Boomerang Strap Yw=24.6 (No. 15)	> 8,000	<u>2,700</u> / .68	5,400/1.25	
5	MCS and OPW Fold Lug (No. 31/40)	> 8,000	<u>4,900</u> / 1.23 <u>2,800</u> / .70	9,800/2.45 5,600/1.40	Lug Hole Lug Shank
6	MCS Skin at Rear Spar, Rear Spar Cap Yw 53.7 (No. 18)	8,000	<u>3,050</u> / .76	6,100/1.53	
7	MCS BL-0 at R Spar (No. 10)	NR	<u>4,150</u> / 1.03	8,300/2.08	
8	MCS BL-0 5th Spar (No. 9)	NR	<u>4,800</u> / 1.20	9,600/2.40	Strap Fail at 1,500 hrs.
9	MCS LMR Skin Y=32 (Item No. 1)	NR	<u>6,100</u> / 1.53	12,200/3.05	

NR - If safety limit > 8,000 rework from economic limit not reqd.
 * Requires wing removal
 ** Damage Index = $\frac{\text{Fit hrs Equivalent Baseline}}{4,000}$
 a_p = flow length @ inspection period
 a_c = critical flow length
 (1) Subsequent to inspection

Damage Index set to equal 1.00 @ 4,000 hours for convenience.

FIGURE 5-2

RECOMMENDED INSPECTION/MODIFICATION INTERVALS FOR CRITICAL ITEMS (EQUIVALENT BASELINE SPECTRA)

INSPECTION LEVEL:	ORGANIZATIONAL OR INTERMEDIATE	DEPOT LEVEL	ORGANIZATIONAL OR INTERMEDIATE	DEPOT LEVEL	ORGANIZATIONAL OR INTERMEDIATE	DEPOT LEVEL	ORGANIZATIONAL OR INTERMEDIATE
DAMAGE INDEX (3):	0.25	0.50	0.75	1.00	1.25	1.50	1.75
TIME (HOURS):	1,000	2,000	3,000	4,000	5,000	6,000	7,000
CRITICAL ITEM (2):							
PYLON	X	X	X	X	X	X	X
400 BHD		X (1)				X	
Y _W = 24.6		X		X		X	
LUG SHANK			X			X	
LUG HOLE					X		
Y _W = 53.7			X			X	
Y _W = 32.2				X		X	
BL-9				X			

NOTES: (1) MODIFICATION OF 1.50 DIA LUG HOLE (AIRPLANES 1 THROUGH 391) IS REQUIRED, FOR AIRPLANES 392 AND SUBSEQUENT INSPECTION OF 1.75 DIA IS REQUIRED

- (2) PYLON - WCS LOWER SKIN, INBOARD PYLON POST (ITEM 3 AND ITEM 7)
 400 BHD - BULKHEAD STA 480, WING AFT ATTACH LUG, (ITEM 58) 1.50 DIA (AIRPLANES 1 THROUGH 391) AND 1.75 DIA HOLE (AIRPLANES 392 AND SUBSEQUENT)
 24.6 - WCS LOWER SKIN, WING ATTACH LUG, Y_W = 24.6 (ITEM 14 AND ITEM 15)
 LUG SHANK - WCS, WOP FOLD LUG Y_W = 135.2 (ITEM 31/40) LUG SHANK
 LUG HOLE - WCS, WOP FOLD LUG Y_W = 135.7 (ITEM 31/40) LUG HOLE
 Y_W = 53.7 - WCS LOWER SKIN, REAR SPAR AND REAR SPAR CAP (ITEM 18)
 Y_W = 32.2 - WCS LOWER SKIN, 5TH SPAR Y_W = 32.0 (ITEM 1)
 BL-9 - WCS LOWER SKIN, CENTER SPICE, REAR SPAR (ITEM 10): WCS LOWER SKIN 5TH SPAR SPICE (ITEM 9)

(3) DAMAGE INDEX - $\frac{\text{TIME (HOURS) EQUIVALENT BASELINE}}{4,000}$

FIGURE 5-3

Correlating the damage index to new requirements updates from the L/ESS program may be straightforward. For example, assume the original FSMP called for an inspection of structural location A at damage index (DI) multiples of .30. If the operational usages of the airplane noted (from the L/ESS) reveal that location B is in fact more critical than location A and it should be inspected at DI intervals of 0.20, then the structural manager will revise his equivalent of Figure 5-2. It is entirely satisfactory for the maintenance actions to be referenced to the periodically reported DI.

5.2 FSM IMPLEMENTATION

The present vehicle for accomplishing the FSMP objective is the Air Force Technical Order (TO) system. The primary documents applicable to the FM activities (discussed in detail in the Task I Report) are:

- o Structural Repair Instructions, TO-3
- o Aircraft Scheduled Inspection and Maintenance Requirements, TO-6
- o Nondestructive Inspection Procedures, TO-36
- o Aircraft Structural Integrity Program, TO-38 (new)

The TO-3 tells the maintenance organization how to make repairs and rework of the structures; TO-6 tells when to do the routine, isochronal inspections; and TO-36 tells how to inspect. The how to inspect is the key to the effectiveness of the entire maintenance program. In order to preserve a high level of flight safety and economic optimization, the TO-36 must detail the latest inspection tools and techniques. (The TO-38 is discussed below.)

The overall inspection capabilities of the Air Force and industry contractors are relatively unimpressive. This is not because of the skill level of the personnel involved, but is due to the state of the inspection art coupled with the time and environment constraints imposed for a given inspection. As will be discussed in Section 5.8, there is a wide range of

inspection capability that varies with parameters such as whether the inspection is focused, made in the laboratory, etc. In any event, the general inspection capability of the Air Force maintenance personnel is as good, if not better, than that of the contractor industry members. It is also true that since there is some variation in the confidence and capability of individual operational maintenance activities, it is recommended that the decision on where to perform a given maintenance action be left to the user of the airplane in question. That is, if the maintenance management at the wing or squadron level believes that a given action can be satisfactorily performed at a low level, then it should be allowed. This freedom on the part of the user will greatly enhance economics and operational readiness considerations.

It is further recommended that all the ASIP/FM maintenance action parameters be located in one document for all airplanes. A new TO is being created to further divide this information. In fact, the ASIP maintenance action parameters and data for the A-7D (and other airplanes) is being split between the TO-3, -6, -36, and (the new) TO-38. This distribution of the information is not optimum. the TO-38, as being published for the A-7D, is a document that presents some history and philosophy of ASIP, and describes the installation and servicing of its IAT instruments. This definition of the objective of the TO-38 results from an interpretation of MIL-M-87138. It is recommended here that the TO-38 should be a document that contains all ASIP/FM maintenance action descriptions. If this were to be the case, all ASIP/FM pertinent information would be in one document instead of four.

Another shortcoming of the FSMP function peculiar to the A-7D is the timing. The A-7D ASIP program was completed in 1977. The documents mentioned above have yet to be issued (or revised) to reflect the findings of the study. It is then recommended that the time lag between the discovery of critical points and their attendant inspection requirements be shortened. This is in the interest of flight safety. It is further known that required

inspections are not always carried out within the prescribed time periods. For example, the safety limit has been exceeded several times on the A-7D before inspections were performed. This is assumed to be the case for all airplanes: safety is sacrificed for operational readiness particularly where the operational commands believe there is a large margin of safety built into the schedules.

5.3 ECONOMIC OPTIMIZATION

The principal task of the force structural manager is to provide directions to the user and maintenance support activities that will result in optimization of economics without compromising flight safety. It appears that to accomplish this mission, a general knowledge of the effectiveness of the Air Force inspection capabilities and rework activities and their impact on structural failures would be indispensable.

This discussion of failure rate analysis (FRA) is included as an example of information that a force structural planner needs. The material is intended to be essential qualitative in nature in that no conclusions should be drawn with respect to the absolute numbers presented. However, the data is quantitative in the sense that reasonable values were required for the successful calculations of trends.

The FRA discussion is concerned with the fracture mechanics of initial rogue flaws in the A-7D wing attachment lug, a location that is assumed to be critical. The assumption is made that the location is subjected to an adverse environment and that the desired life of the part is 8000 hours.

Figure 5-4 is assumed to be the crack propagation response of the lug to a severe usage spectrum. Shown is an initial crack length of .05 inch, the official criteria for the A-7D. the critical crack length is based on a residual strength analysis such as specified by MIL-A-83444. Figure 5-5 displays the net effect of the criteria given by MIL-STD-1530A as applied to

A-7D WING ATTACH LUG

ROGUE FLAW GROWTH

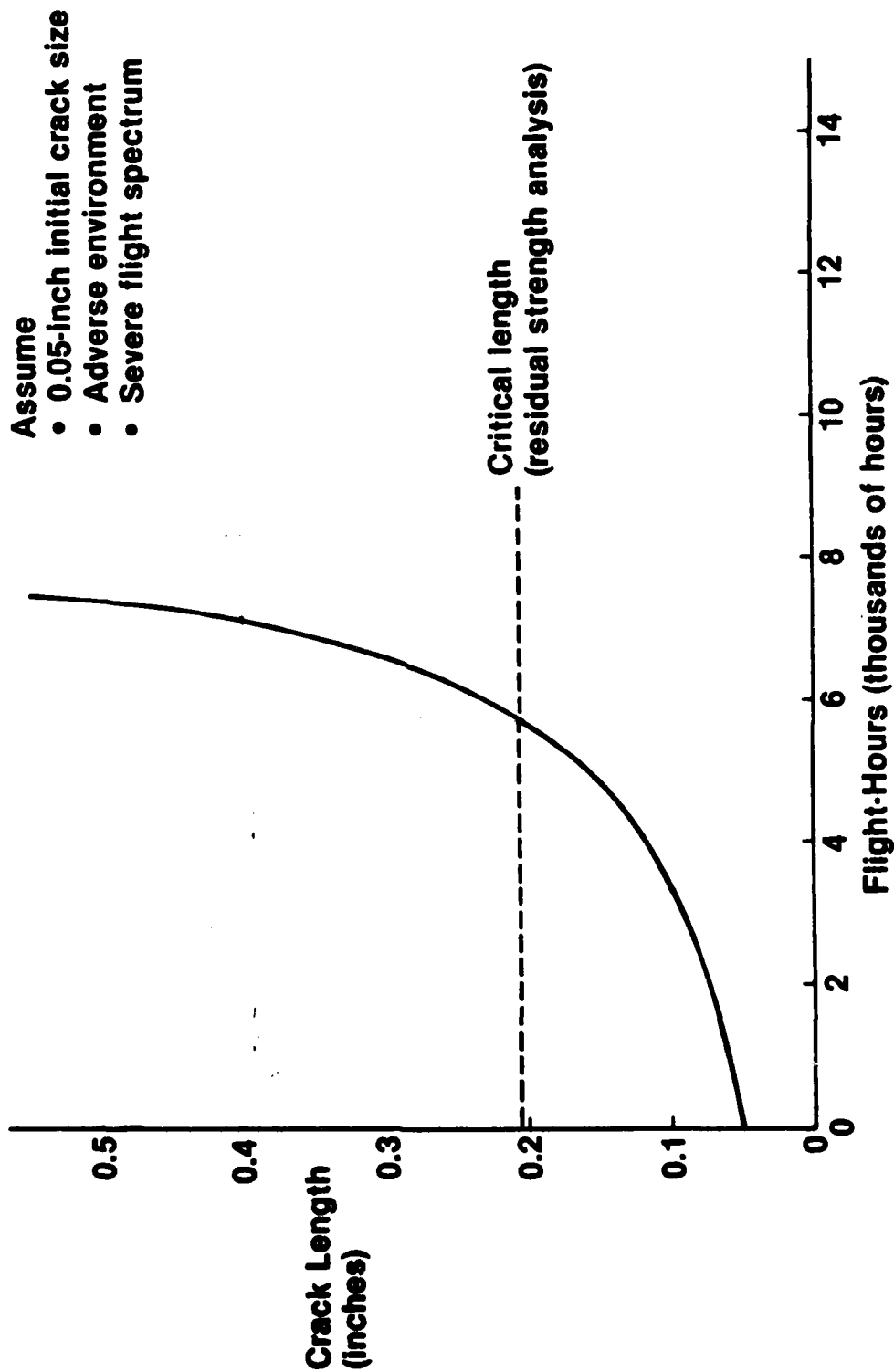


FIGURE 5-4

A-7D WING ATTACH LUG

ROGUE FLAW INSPECTION WITH 100% CRACK DETECTION

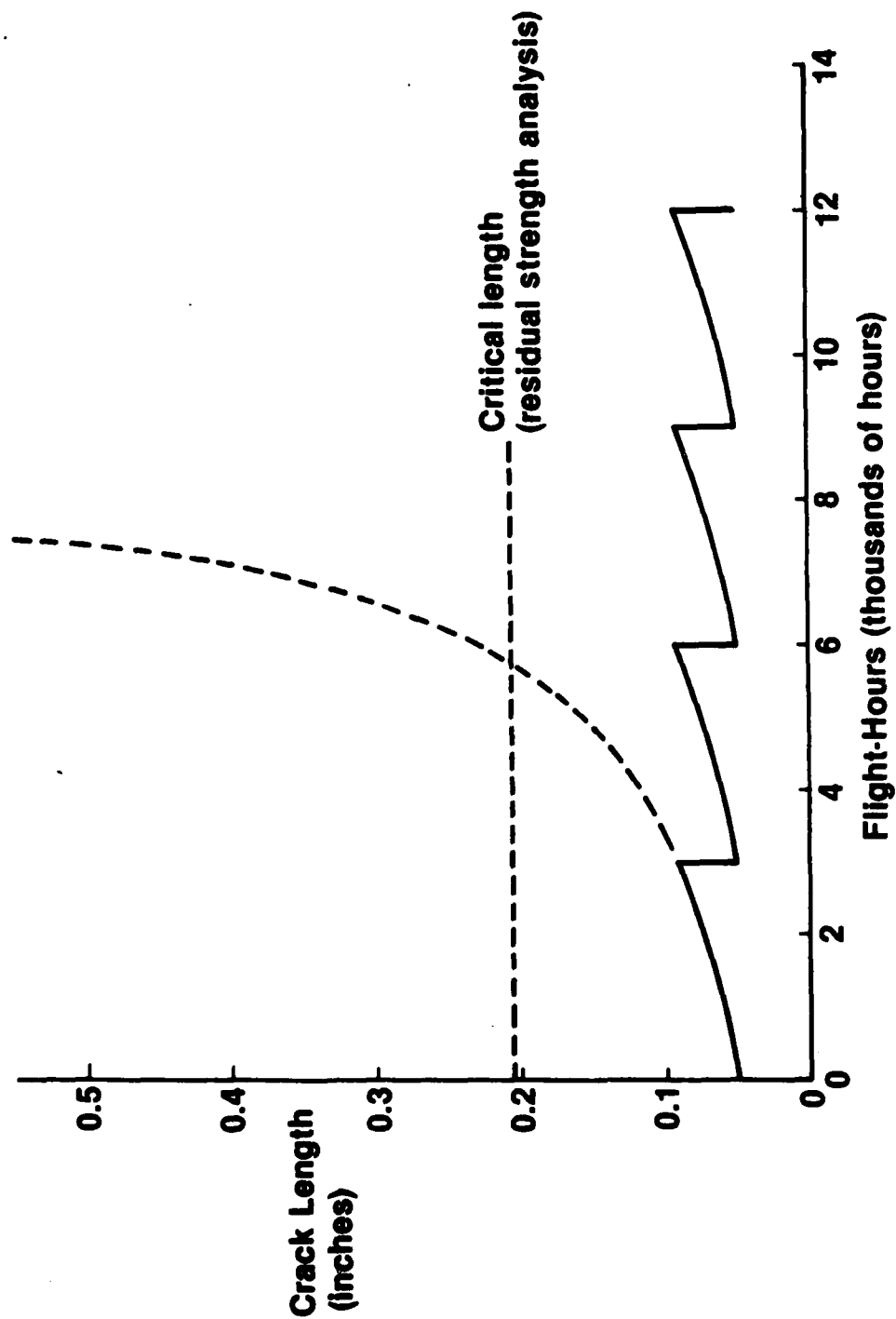


FIGURE 5-5

the A-7D. That is, it is assumed that a possible initial .05 inch flaw will grow according to usage until an inspection is performed. At the inspection, the flaw is either treated or found to be imaginary. After the inspection (and maintenance action) the flaw is assumed to again be back to .05 inch and the process begins anew. The assumption implied by Figure 5-5 and MIL-STD-1530A is that an inspection reveals all the cracks present in the structure. This is not true but the non-conservatism implied is somewhat offset by the assumption of a .05 inch initial flaw.

The structural manager is aware that inspections do not detect all the flaws in a structure. Only inspections performed under laboratory conditions provide a high probability of small flaw detection. While few inspections performed by the Air Force maintenance personnel are under laboratory conditions, a majority of the inspections are "focused". This means that a local area is being examined in detail, and this emphasis improves the probability of detection.

Figure 5-6 represents data (taken from Reference 2) that summarizes the non-destructive inspection (NDI) capabilities of several common inspection techniques. On this figure the quantity m is defined in the following manner:

Let a_1 be the minimum flaw size that can be detected.

Let a_2 be the minimum flaw size beyond which the flaw can be detected with certainty. The probability of detecting a crack of length x ,

$P(x)$, is defined as:

$$\begin{aligned}
 P(x) &= 0 && \text{for } x < a_1 \\
 &= \left(\frac{x - a_1}{a_2 - a_1} \right)^m && \text{for } a_1 \leq x \leq a_2 \\
 &= 1 && \text{for } x > a_2
 \end{aligned}$$

CRACK INSPECTION CAPABILITIES

(PER WOOD, SHINOZUKA, YANG, et. al.)

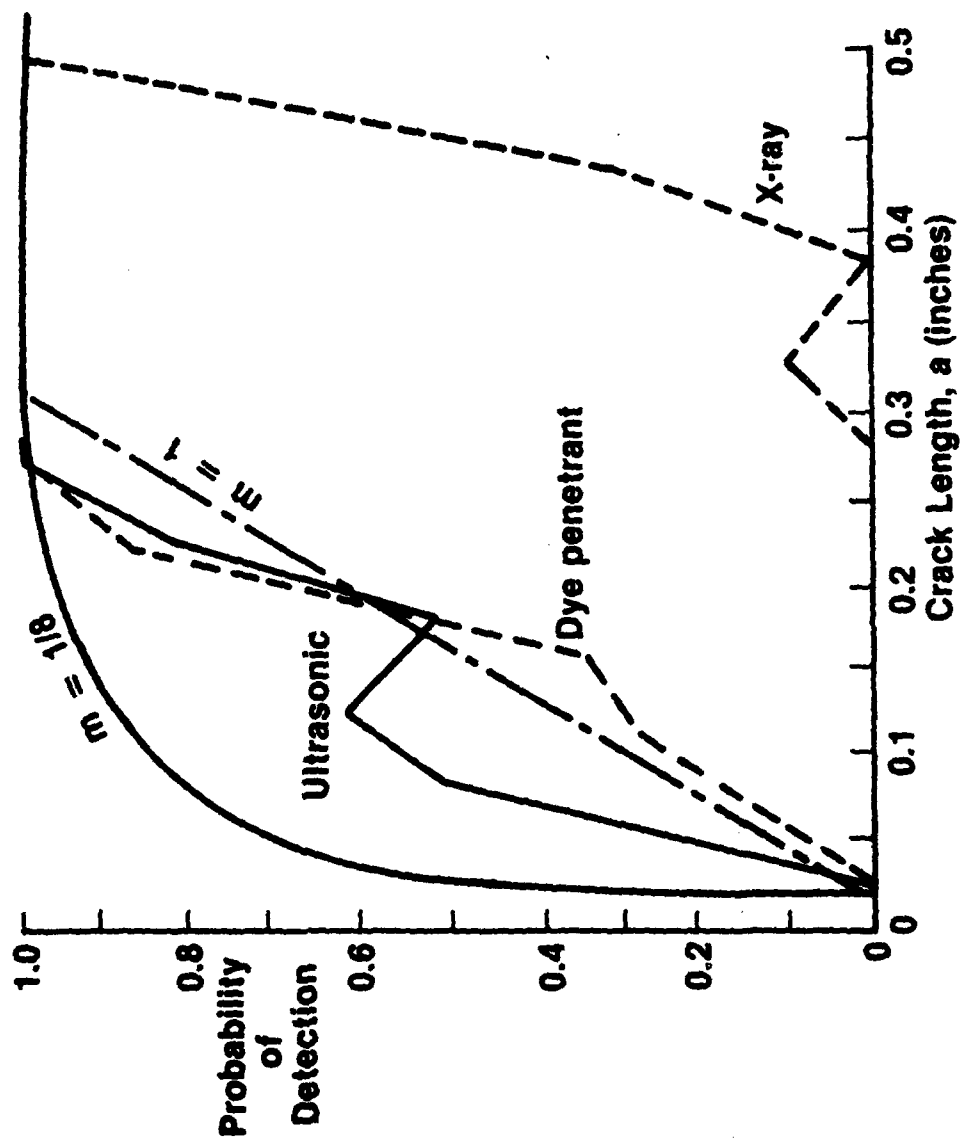


FIGURE 5-6

The value of $1/8$ for m corresponds roughly to laboratory inspections. The straight line of $m = 1$ is used in the subsequent discussions and is considered to be an acceptable average of the methods shown in Figure 5-6. It is expected that Air Force focused inspection will have the capability somewhere between $m = 1$ and $m = 1/8$. The assumption of an m different than 1 will change the numbers shown below, but the trends will be preserved.

Based on the assumed NDI capability reflected by $m = 1$, Figure 5-7 presents the probability of not detecting an initial .05 inch flaw at successive inspections at each 2000 flight hours. After the first 2000 hours, there is a probability of .81 that the flaw will not be detected. After the flaw has grown during the next 2000 hours, there remains a 55% chance that the flaw will not be detected, etc. Figure 5-8 (derived from methods presented in Reference 13) shows the net probability of attaining critical crack length in 8000 hours based on the capability of Figure 5-6. The horizontal scale represents varying frequency of the inspections. The interpretation of the horizontal scale is the following: for the 2000 hour inspection intervals, an inspection is performed at 2000, 4000, and 6000 hours; the 3000 hour point indicates inspections at 3000 and 6000 hours; the 4000, 5000, and 6000 hour points indicate one inspection at these times since these values cannot be doubled and be less than the 8000-hour life. This type of data may be generated to determine the optimum isochronal inspection intervals for any locations.

Another more realistic investigation into the probability of failure subject would be to assume that the airplane is subjected to a distributed usage ranging from mild to severe, that the initial flaws in a structure are also subject to some distribution of sizes, and the failing crack length is a distribution. Figure 5-9 is a schematic of crack propagation showing a distribution of initial crack lengths, a distribution of usage severity, and a distribution of the definition of the critical flaw length. This distribution

ROGUE FLAW INSPECTION WITH NDI CAPABILITIES

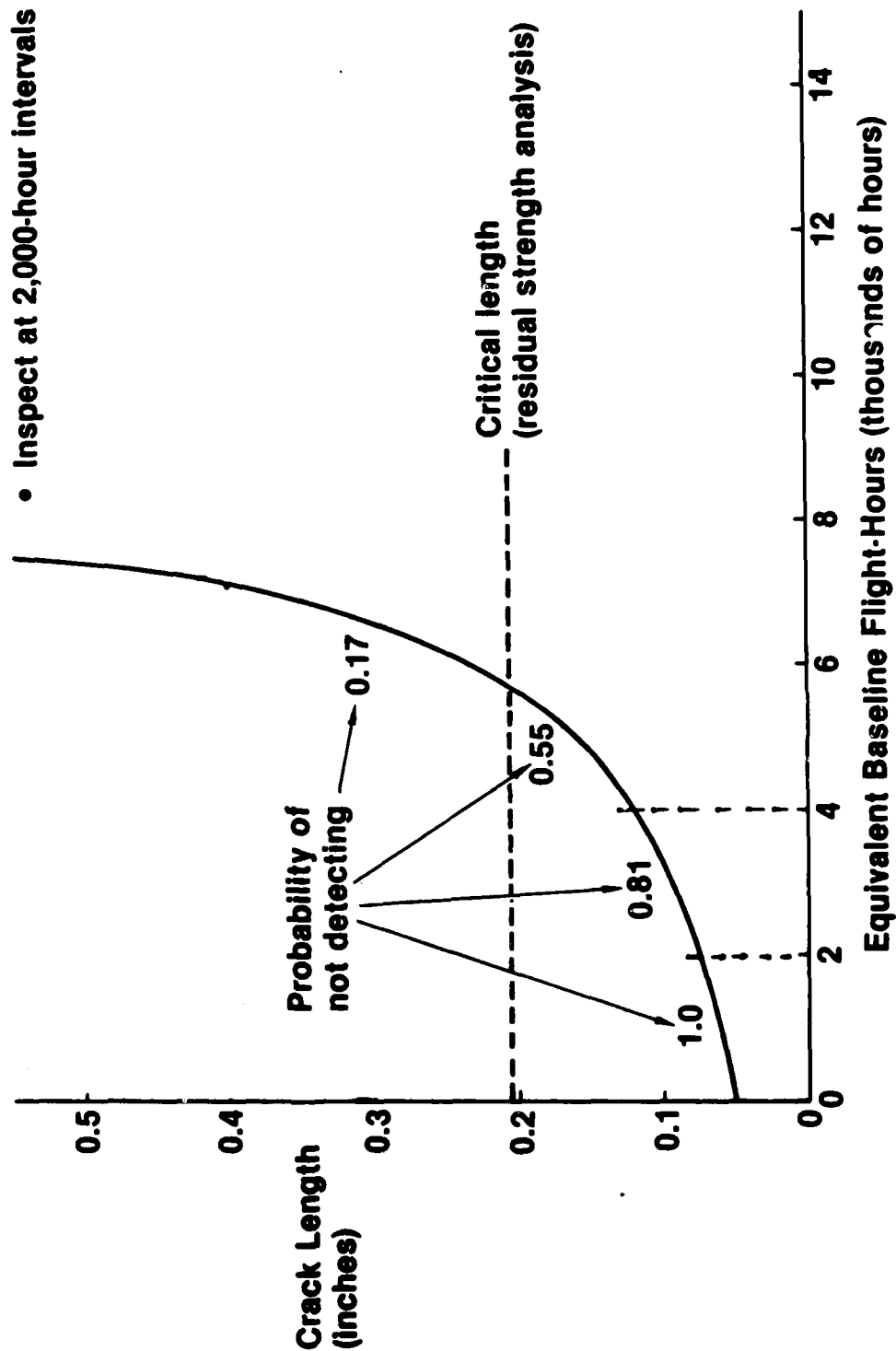


FIGURE 5-7

CRACK PROBABILITY EXISTENCE FOR VARIOUS INSPECTION TIMES

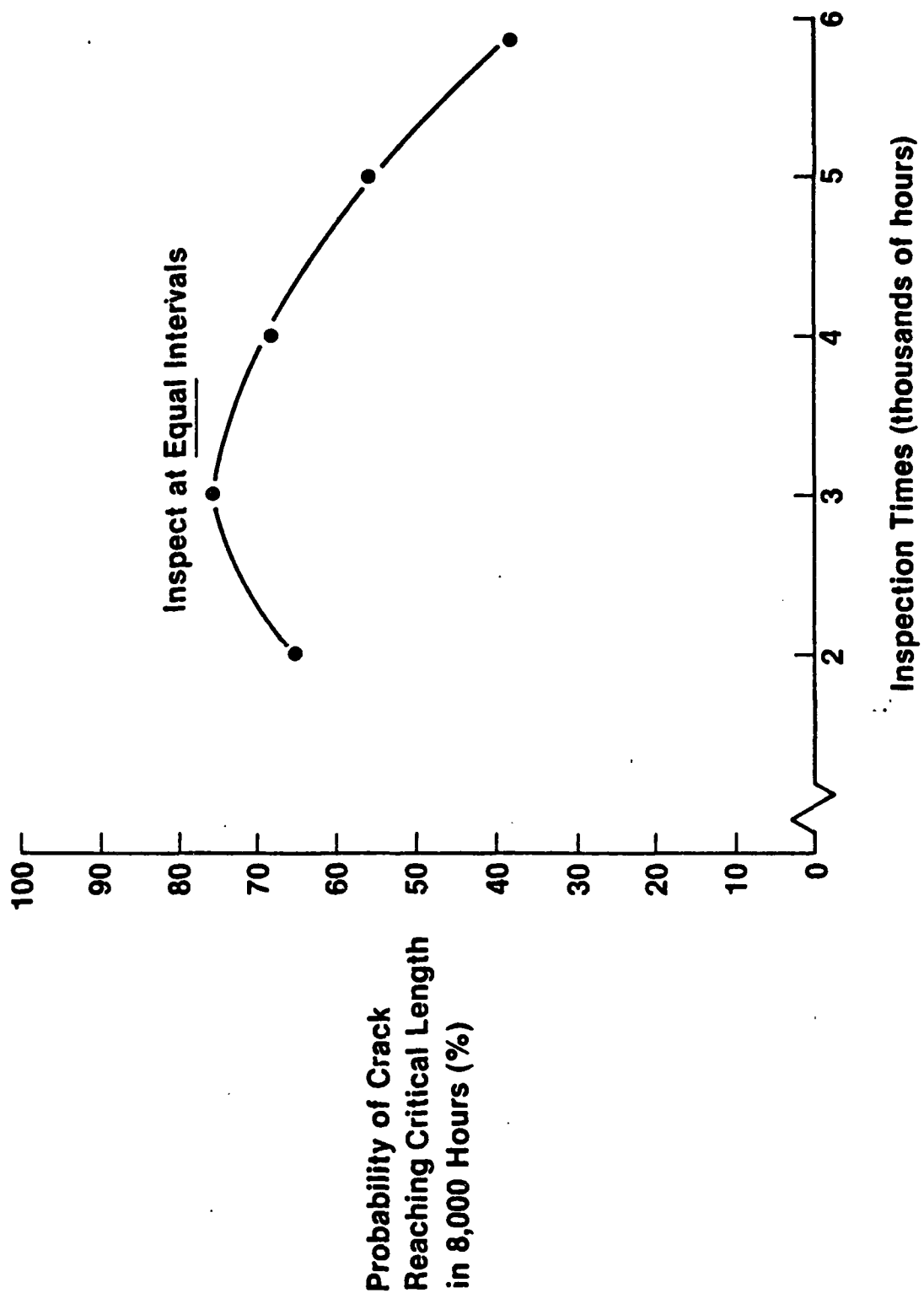


FIGURE 5-8

A-7D WING ATTACH LUG **DISTRIBUTION OF FLAWS - DISTRIBUTION OF USAGE**

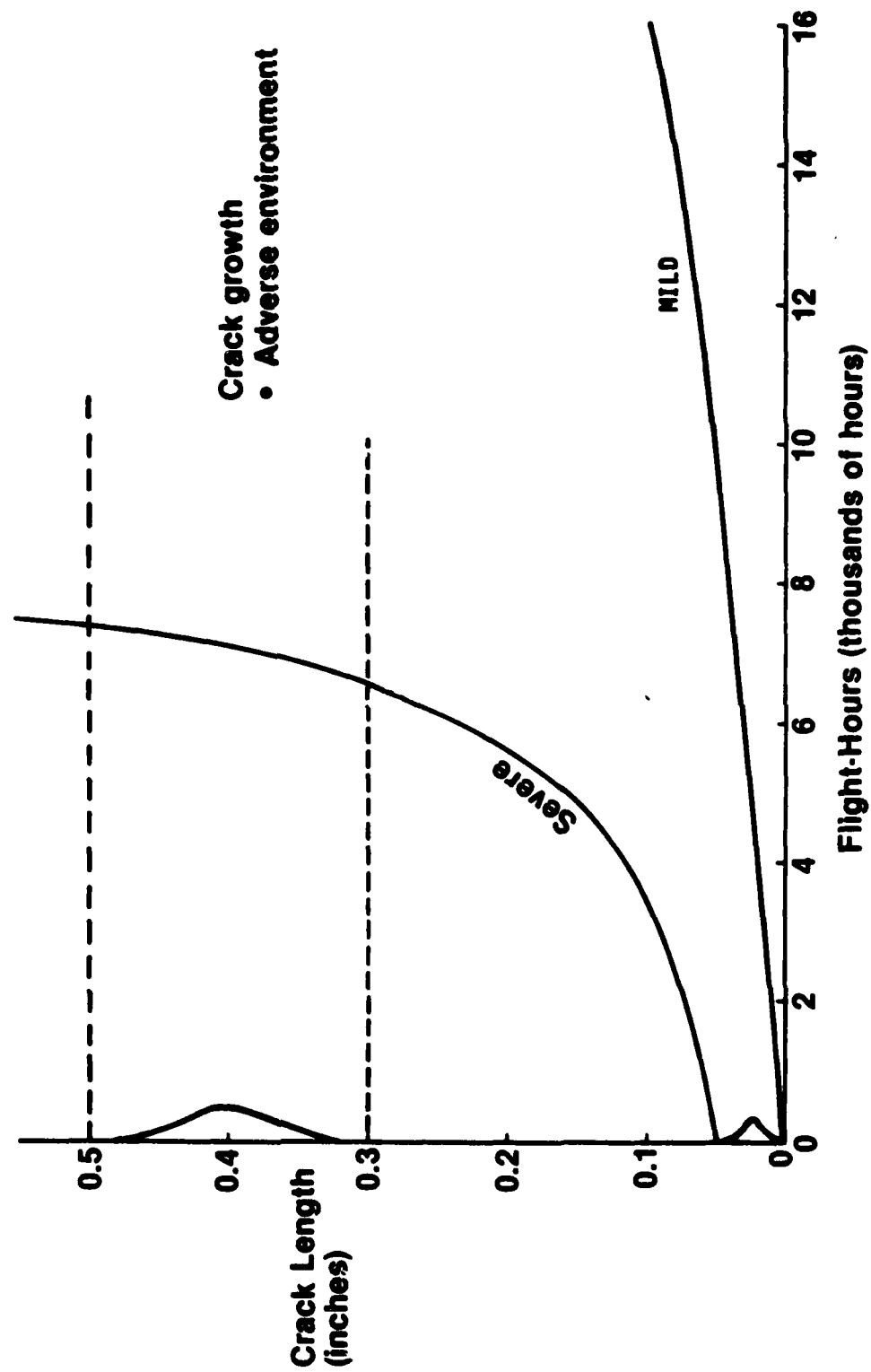


FIGURE 5-9

of critical length has been verified by test. The distribution of initial crack length is characterized by a maximum flaw of .05 inch and a minimum of .001 inch. A rogue flaw of .05 inch has been calculated to occur once in 40,000,000 flaws.

Figure 5-10 presents probability of failure data versus airplane flight hours. Shown is the probability of failure of the wing lug with no inspections whatever performed. The lower curve presents the failure probability for inspections performed at 2000, 4000, and 6000 hours. As the flight time approaches 8000 hours, the inspection intervals are decreased to where they occur at 7000 hours and 7500 hours.. It is seen from this figure that there is little return on inspection effort until the flight time approaches about 90% of the design value.

The data of Figure 5-10 may be revised slightly if the probability of failure is calculated as a function of optimized inspections. This is shown in Figure 5-11. An optimized interval is defined as one that will vary with the chance of success of detecting the flaws versus a constant multiple of flight time.

Finally Figure 5-12 is shown to give an indication of the "return on investment" of performing inspections. This benefit of inspections return is given in terms of change in probability of failure. For example, the change in probability of failure in going from one inspection in 8000 hours to two is nearly 0.5, a large change. However, the benefit of performing a third inspection is only a change of approximately .05 in probability of failure. An interpretation of this statement is that the effectiveness of the third inspection is an order of magnitude less in terms of safety of flight than was the second inspection. The horizontal scale could well represent dollars expended. For example, the cost of removing an A-7D wing for this inspection is approximately 200 man hours.

Considering the expense of many inspection, it is recommended that (1)

A-7D WING ATTACH LUG

PROBABILISTIC ROGUE FLAW ANALYSIS - EFFECT OF INSPECTIONS ON FAILURE PROBABILITIES

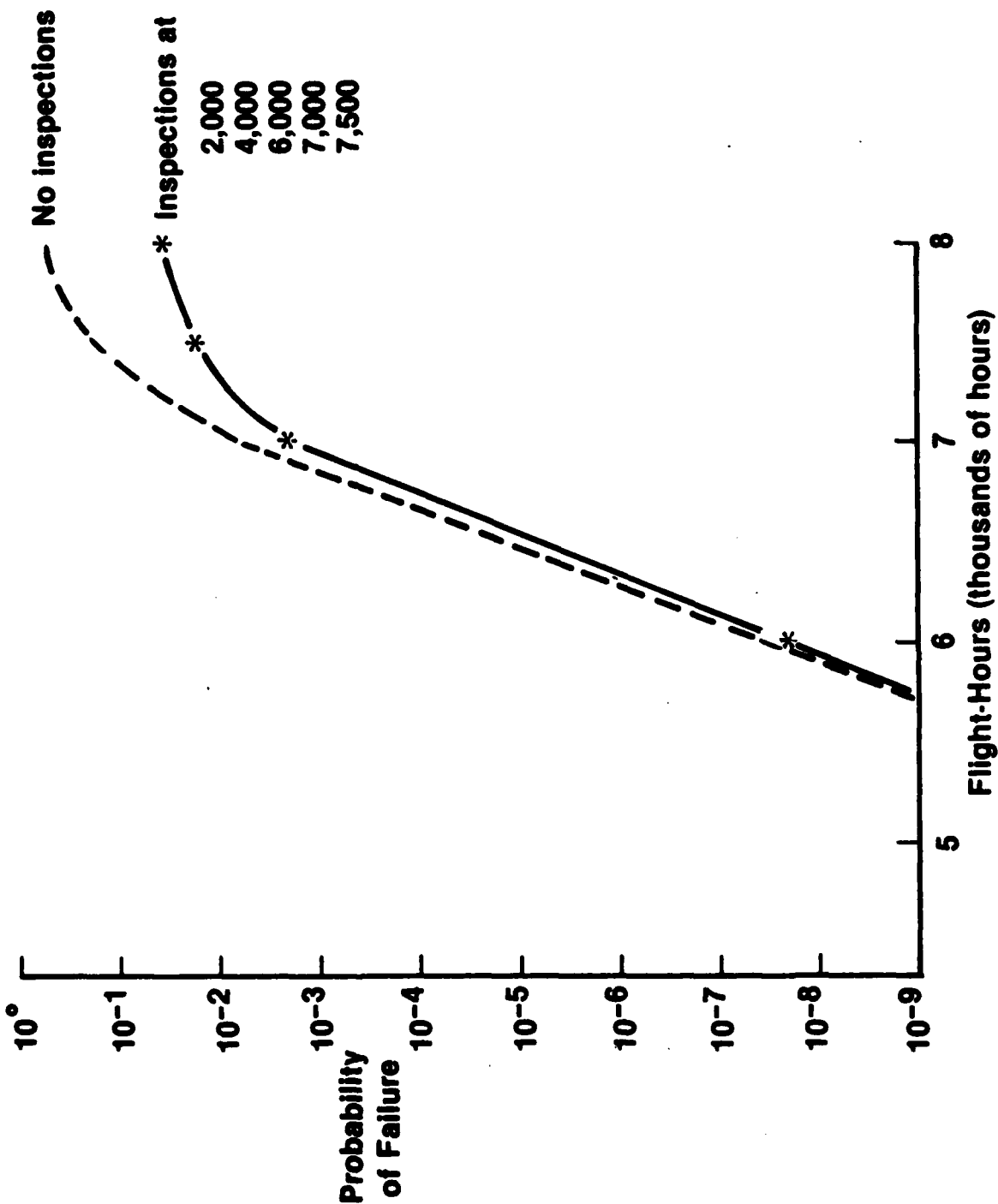


FIGURE 5-10

A-7D WING ATTACH LUG

PROBABILISTIC ROGUE FLAW ANALYSIS - EFFECT OF OPTIMIZED INSPECTIONS ON FAILURE PROBABILITIES

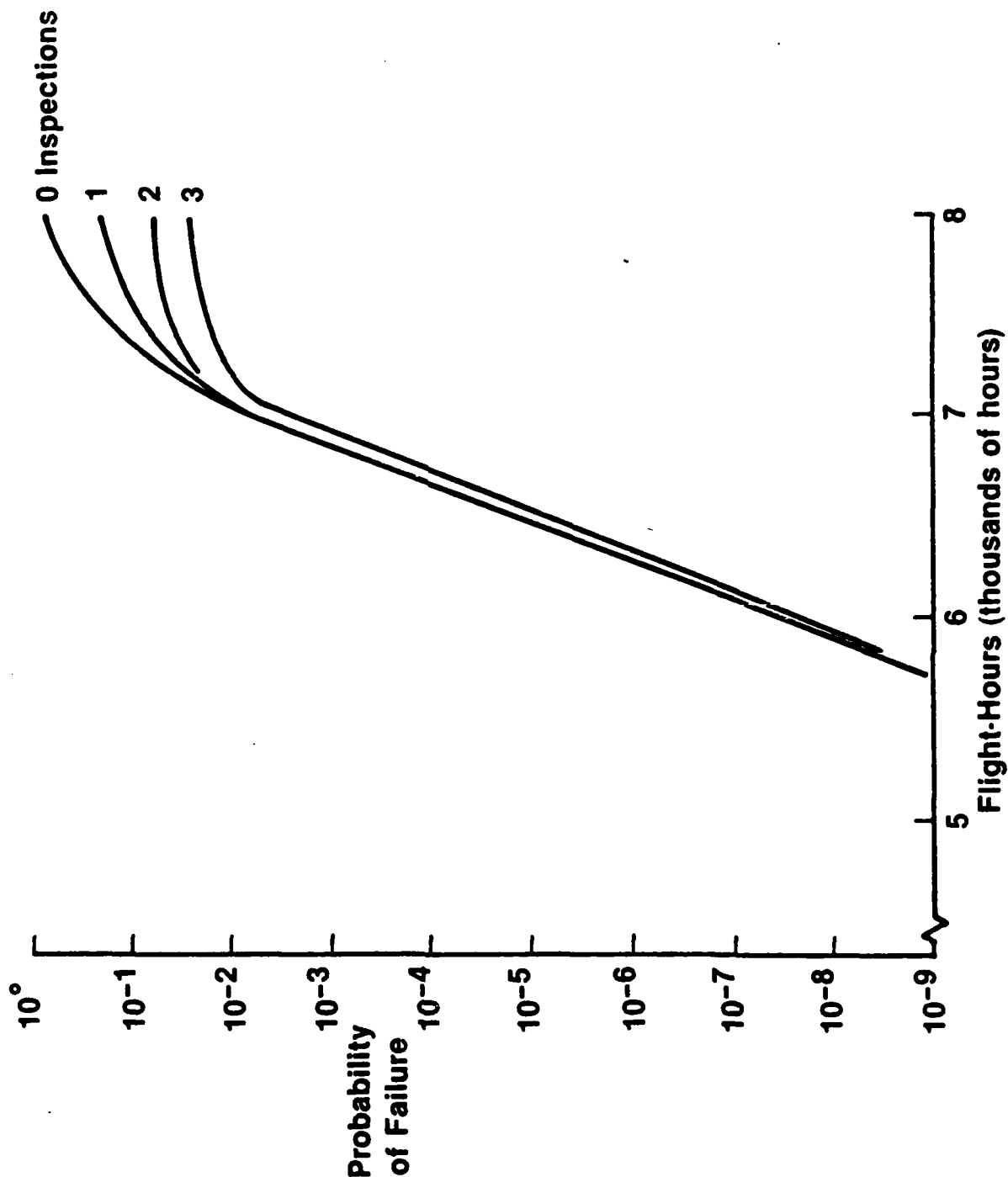


FIGURE 5-11

A-7D WING ATTACH LUG

CHANGE IN PROBABILITY OF FAILURE IN 8,000 HOURS VS OPTIMIZED INSPECTIONS

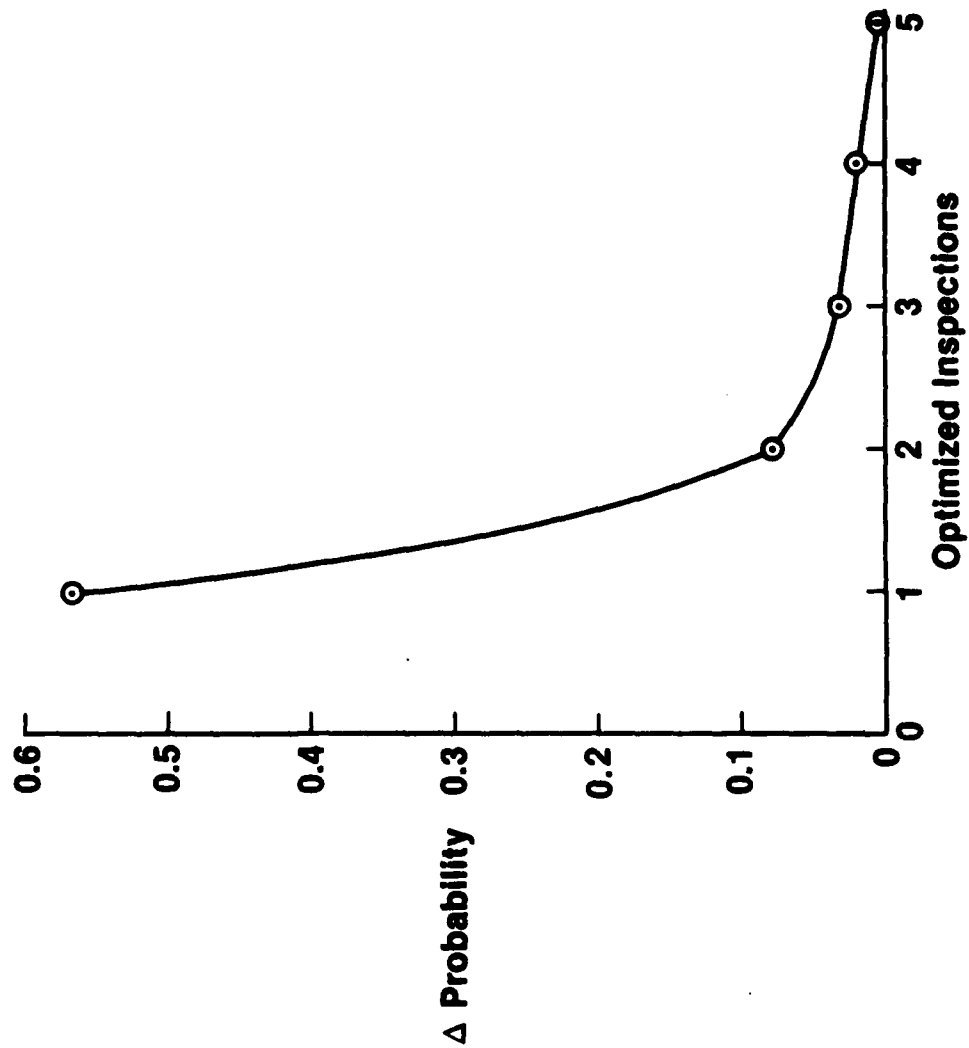


FIGURE 5-12

the inspections be programmed according to some rational probability of attaining a critical crack length analysis, and (2) once an expensive inspection has been undertaken, that the target location be reworked even though a flaw is not found.

It is possible to do meaningful economic studies in pursuit of optimizing force inspections. The force structural manager is charged with providing an operational ready force and a safe force for his pilots. It is studies such as probability of failure investigations that assist the manager in making difficult decisions when forced to decide between safety and readiness.

6.0 INDIVIDUAL AIRCRAFT TRACKING (IAT) METHODS

The purpose of this investigation into the Air Force individual aircraft tracking methods is to produce an objective evaluation of present methods and to propose improved methods. This objective has been met in that there is a discussion of the relative merits of each method at the end of the section. However, it must be stated that some of the final conclusions drawn about the methods are based on information that is not universally accepted. The methods are evaluated on the basis of cost, accuracy, and implementation considerations. Between these three, cost was considered to be least important because of the relatively small expenses being discussed.

For example, it appears to make little real difference whether the IAT function for the A-7D airplane represents 0.11% or 0.14% of the total cost per flight hour for the airplane. On the other hand, a judicious and optimum trade-off between ease of implementation and accuracy may be much more difficult to attain. In fact, these latter elements are related in that the quantity of good data produced is a function of the ease of implementation and the accuracy of the results in a function of the quantity of good data.

Because the methods discussed here are to perform the identical mission, there are several important aspects that will be considered invariant with the method. First, all the methods essentially produce cumulative occurrence-of-events type data. Use of this type of data has been accepted as adequate by the Air Force and many contractors for the IAT function. A liability with any system or method will always be data loss. Probably the best yield for any method will be on the order of 80-90% good data. The basic premise here is that there will be some data loss and that the gap will be filled using base average usage data. This method is widely used and probably cannot be improved on significantly.

IAT is addressed here as only a part of an overall structural

management effort. Although the discussion of the IAT methods did not have an explicit "L/ESS relationship" factor involved, the chosen method does complement the recommended L/ESS method as discussed in Section 7.0.

6.1 USAGE TRACKING REQUIREMENTS

MIL-STD-1530A states that "The objective of the individual airplane tracking (IAT) program shall be to predict the potential flaw growth in critical areas of each airframe that is keyed to damage growth limits of MIL-A-83444, inspection times, and economic repair times." The achievement of this objective, in effect, requires the capability of determining a current or instantaneous damage state (or damage index, DI) for each force element. This DI information is used by the force structural manager in a variety of ways. the primary and immediate application of the information provides the manager the capability of optimally scheduling the individual maintenance actions required by his force. These actions include airplane inspections, component rework, repair, component replacement, and ultimately, airplane retirement. Efficient and educated programming of these maintenance events is a necessity for the availability of an operationally ready and safe force of airplanes.

A longer range objective and requirement of the IAT program is to provide the capability of estimating the force damage rates and resulting volume of required maintenance actions. This capability is critical to providing for the availability of financial, personnel, spares, and facility resources required to perform the maintenance functions. Often these resources need to be planned years in advance. The ability to make reasonably accurate estimates of the force damage rates comes in part from the close scrutiny of IAT data. The IAT data should have the features required to reveal at least gross usage changes within the force. An efficiently designed IAT system can have a decidedly favorable impact on the life cycle cost of an

airplane weapons system.

6.2 IAT METHODS

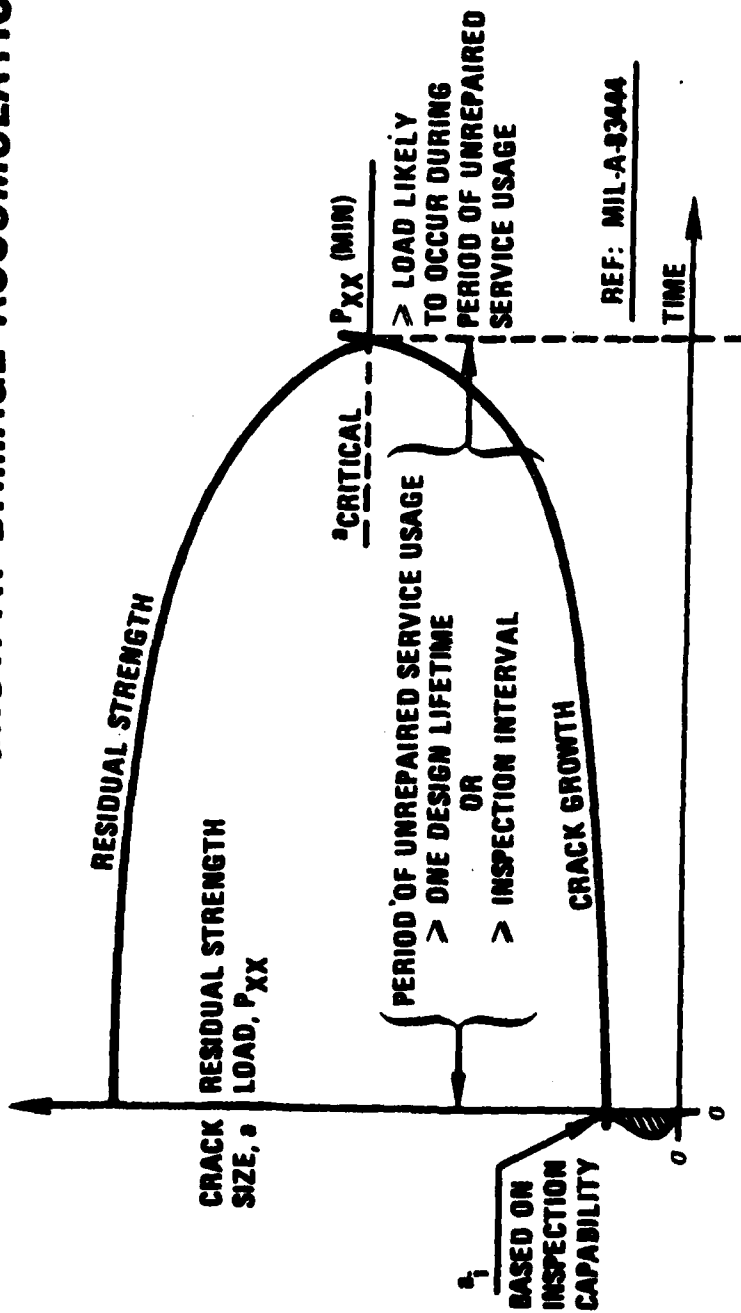
6.2.1 IAT Parameters

The basic parameter of the IAT function is structural crack length. This definition of the fundamental quantity is effectively prescribed by the MIL-STD-1530A requirements that the methods of fracture mechanics be employed in the evaluation of airframe structure fatigue life. Crack length may be considered the fundamental airplane structural integrity parameter (in the fatigue sense) for two reasons. First, sub-critical crack propagation (after some initiation time period) is an invariant characteristic of airframe repeated loadings. Damaging repeated loads always result in crack propagation in structure. Secondly, the remaining strength of a part may be related to the crack length. Therefore, knowledge of the crack length provides an insight to the remaining usefulness of the structure. That is, crack length defines a damage state. Figure 6-1 is a schematic showing the variation of the useful residual strength of a part as a function of the crack length. This presentation reflects the criteria of MIL-A-83444. The critical crack length mentioned on this figure is defined as the value when the structure has the ability to sustain some specified load.

Therefore, the entire IAT machinery is designed to determine, directly or indirectly, the crack length at critical structural locations. For conservatism, the existence of an initial crack or flaw in the structure is assumed. This relatively small initial flaw may be assumed due to manufacturing or fabrication damage; however, the repeated loadings experienced by the structure during airplane operations may cause the flaw to grow to a dangerous state.

As seen from the report of Task I describing the IAT state of the art, there are no methods in use that allow the direct determination of a crack

SCHEMATIC OF SAFETY GOALS FOR NEW STRUCTURE BASED ON CRACK GROWTH DAMAGE ACCUMULATION



REF: AFFDL TR 75-32

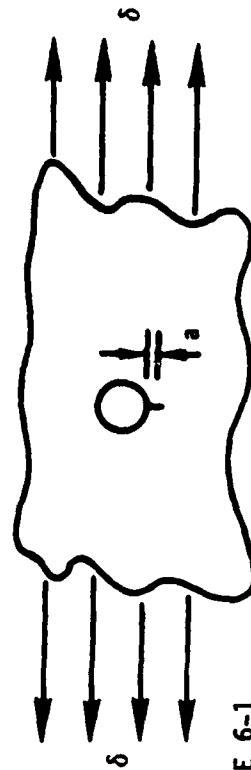


FIGURE 6-1

length in an arbitrary structural element. It is possible to determine an exact crack length using dye penetrant, x-ray, or ultrasonic methodology for a particular case. However, this is virtually impossible for a critical location that happens to be buried deep in the airplane and surrounded by fasteners, fuel cells, systems, etc. In the absence of the ability to directly determine the crack length, the basic problem of IAT reduces to that of employing the best indirect methods possible. These indirect methods rely heavily on test, analysis, and statistics.

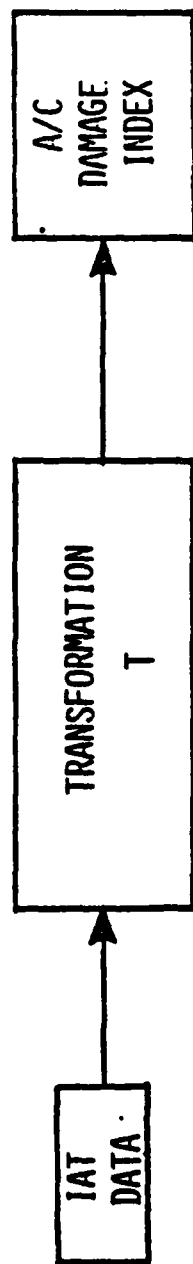
In an attempt to analyze the stages involved in the process of obtaining the airplane general damage state from IAT data, the chart of Figure 6-2 will be considered. The general transformation that takes the IAT raw data into a quantified airplane damage index may actually be thought of as the product of five subordinate transformations to be discussed below. Often, one or more of these operations may be implicit or hidden, but all IAT systems effectively use them all. These transformations or operations will form the basis for grading each IAT method considered here for the attack/fighter/trainer (A/F/T) case.

6.2.2 IAT Monitoring Techniques

Because of the inability to determine directly the crack length at any required structural location, the methods presently in use (and those seen for use in the future) depend on relating exceedances of load, stress, or strain to crack length. This dependence does not necessarily represent a major defect since highly accurate results are possible using only exceedance data. For purposes of the following discussions, it will be assumed that the structural strain is the one basic quantity among the three interchangeable entities of load, stress, and strain. Strain represents the effect of the load or stress and generally may be easily calculated from them.

Referring to Figure 6-3, it is seen that the first transformation T_1

IAT DATA FLOW



$$T = \begin{bmatrix} T_1 & T_2 & T_3 & T_4 & T_5 \end{bmatrix}$$

FIGURE 6-2

converts the IAT data into a strain spectrum for the IAT reference location in the airplane and transformation T_2 produces a damage at that location. Transformation T_3 relates the strain at the monitored (or reference) location to the strain (or load) at other locations in the airplane. This transfer of damage is one of the most critical and tenuous of all and will be discussed in detail below. Transformation T_4 is similar to T_2 in that each of the remote strains is converted to a local damage. Transformation T_5 converts the damage data from the various locations to some composite damage index for the entire airplane. Presently this transformation may be considered essentially trivial. That is, for some airplanes the ultimate or composite DI is calculated by simply taking the ratio or difference of two numbers. In an attempt to provide for possible future developments, T_5 is considered non-trivial. For example, if one is considering a futuristic case involving composites or other advanced materials, this transformation may be extremely involved in order to address ply delamination, corrosion, real time effects, stiffness degradation, visco elastic effects, etc.

Figure 6-4 illustrates the definitions of the basic IAT transformations for a hypothesized airplane assumed to use the counting accelerometer as the tracking variable. Transformation T_1 will provide for the activity indicator output to be converted to structural strain. For the CA, this may be a relationship that approximates the strain using averages for the mission variables such as weight, Mach number, altitude, etc. For the A-7D airplane, this is a linear function.

Transformation T_2 takes the spectrum of strain exceedances at the reference location and uses the crack growth response of the structure, as established by test, to express damage as a function of strain exceedances. In practice, the equivalent strain exceedance data will be organized into flight-by-flight sequences before testing. Several different spectra will be

IAT TRANSFORMATIONS (GENERAL CASE)

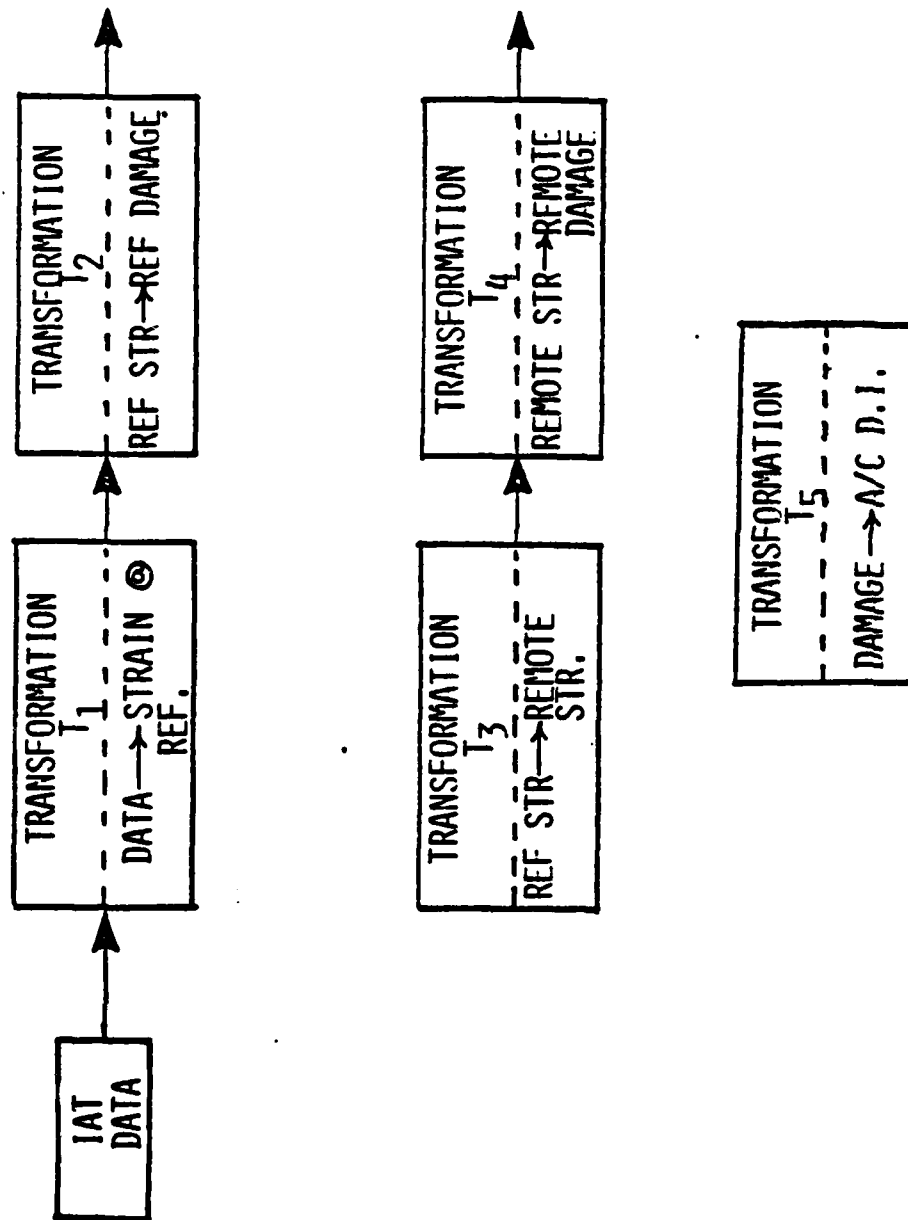


FIGURE 6-3

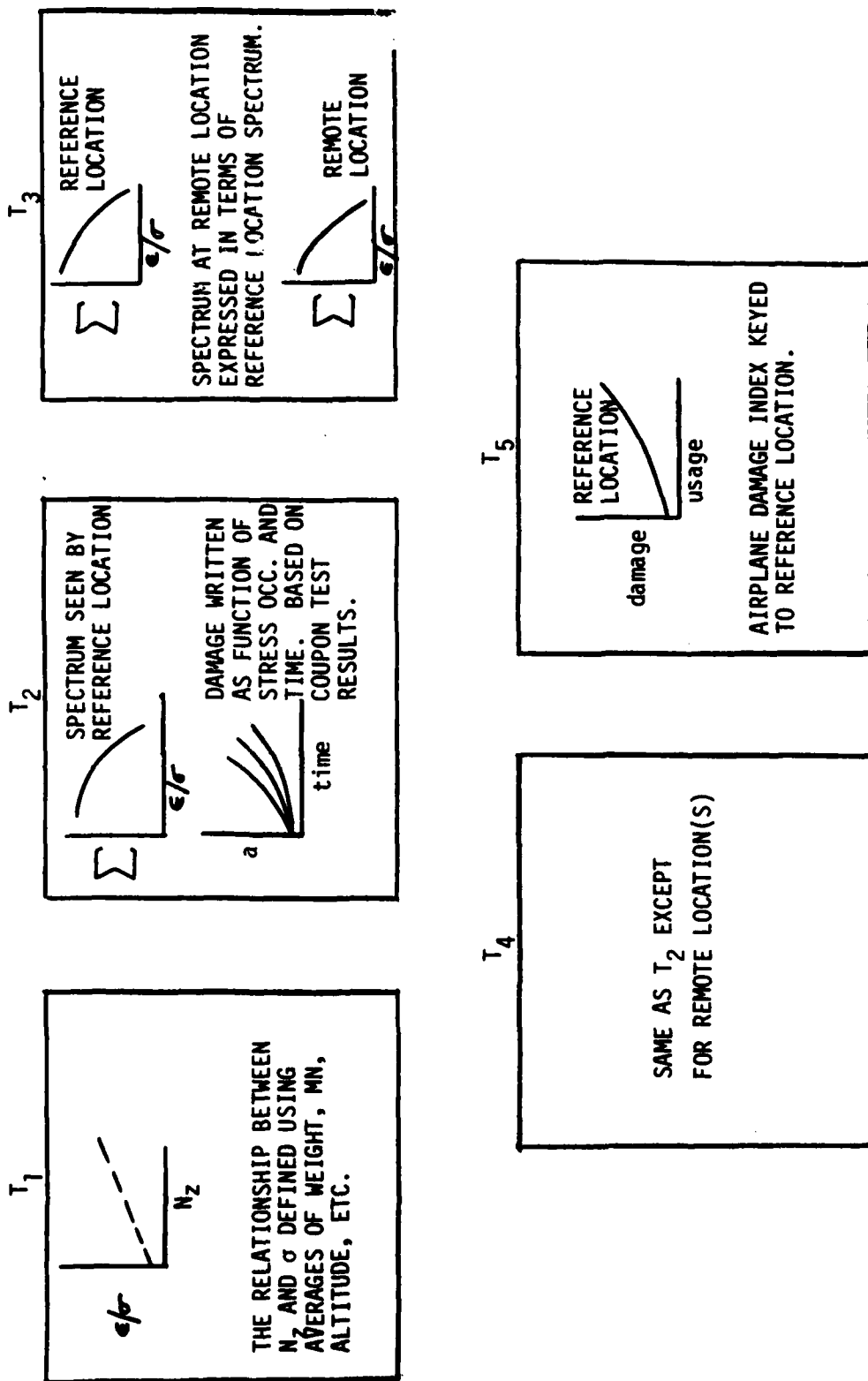


Figure 6-4 Schematic of IAT Transformations

tested to enhance the quality of the resulting regression equation that defines the damage. In the case of the A-7D, it has been found (Section 6.2.2.1.3) that the function defining the damage index also includes flight time as a variable.

Transformation T_3 provides knowledge of the stresses or strains at locations remote to the reference. This type information is based on analysis and test to a large extent, but because of the generally large variations in loadings, the operation is termed statistical for purposes of this discussion. Transformation T_4 is similar to T_2 as pointed out above, except it applies to remote locations.

The operation of T_5 will express a damage index for the entire airplane. This damage index will be defined and keyed to the reference location damage.

Figure 6-5 is a matrix that characterizes the methods presently used in the transformations for each of the IAT techniques discussed below. Each method will be discussed relative to the strengths and weakness of the transformation which characterize the technique. The rationale for assigning the total accuracy score to each IAT method will be discussed in the appropriate section below.

6.2.2.1 Counting Accelerometers (CA)

6.2.2.1.1 Advantages and Limitations

The counting accelerometer is operationally the simplest and most straightforward of the activity indicators to be considered here. The device produces cumulative numbers or counts of acceleration discretes that are loaded onto forms for subsequent keypunch and computer processing. The processing can be exceedingly straightforward and direct in producing a damage index when using techniques discussed below. An additional strength of the CA method, from a purely practical point of view, is that it is a checked out

IDENTIFICATION OF IAT TRANSFORMATIONS

METHOD	T ₁	T ₂	T ₃ (NOT SCORED)	T ₄	T ₅
CA	STATISTICAL	TEST/ ANALYSIS	STATISTICAL	TEST/ ANALYSIS	TEST/ ANALYSIS
MSR	-	TEST/ ANALYSIS	STATISTICAL	TEST/ ANALYSIS	TEST/ ANALYSIS
FORMS	STATISTICAL				→
CGG	-	-	STATISTICAL	TEST/ ANALYSIS	TEST/ ANALYSIS
NP/SC	-	TEST/ ANALYSIS	STATISTICAL	TEST/ ANALYSIS	TEST/ ANALYSIS

FIGURE 6-5

system with regard to user personnel familiarity and ease of interface. There are no recorder elements to be changed, adjusted, or maintained on a scheduled basis. The indicating device or transducer themselves may need routine, unscheduled maintenance, however.

As pointed out on Figure 6-5, the T_1 is statistical in nature for the counting accelerometer. The method records the vertical load factor (in g counts) which corresponds to a stress or strain condition in the airframe. However, there are weaknesses associated with this operation. First, there is the problem of non-uniqueness in the transformation. For example, a given load factor in a symmetrical flight condition yields a peak strain state in the reference location, say the wing tension skin. Also produced are corresponding strains in other airplane structure. There may be many other flight conditions, (ones with the same load factor coupled with unsymmetrical flight conditions) that produce the same CA record but an entirely different strain state in the reference location and the remote locations.

A second weakness of T_1 is that the CA method cannot account for variation in airplane gross weight. The strains in commonly critical locations (such as the wing tension skin) are particularly sensitive to the product of the airplane vertical acceleration and the airplane gross weight. Other critical flight parameters for many airplanes is the instantaneous Mach number (MN) and altitude. The MN effect is due to shifts in the wing center of pressure (CP) that occur as the MN varies. This shift in the CP redistributes the wing load and the resulting strain state. The altitude effect is connected with changes in wing flexibility parameters. The counting accelerometer is blind to weight, MN, and altitude. Appendix B contains detailed analytical data that demonstrates this problem. Dramatic changes in fatigue life are seen with major changes in usages and mission parameters.

The counting accelerometer method theoretically must lean on an

effective L/ESS program in order to provide good tracking information. As a practical matter, however, the structural manager will be aware of major usage perturbations that could result in faulty CA data. For example, information on force-wide changes in fuel programming (which can impact gross weight during maneuvers) or airplane re-engine programs (which could affect MN and altitude occurrences) should be called to his attention separately from the L/ESS results.

It also may be true that the T_1 for the CA is much superior in one aircraft model than in others. This quality index for T_1 appears to be a function of the airplane flying qualities, configuration, and location of critical points. These aspects cannot be discussed here in any quantitative detail.

The transformation T_2 is stronger than a purely statistical operation because of the deterministic nature of testing and analysis. It is clear that T_2 is dependent somewhat on statistical elements, because there is always scatter in the crack growth behavior of a specimen exposed to a given strain history. However, this variance is present for any method that determines a damage from strain and will not be discussed in a differential sense.

The transformation T_3 is by necessity a statistical operation. If anything, this transformation is weaker than T_1 . The difficulties of T_3 are similar in nature to T_1 insofar as the non-uniqueness feature is concerned. It is very difficult to predict highly accurate loads in a remote part of an airplane based on the load experience at any one reference point. It is judged that using the methods of statistics, with a large enough number of observations, adequate accuracy may be obtained in the transfer of damage to remote locations.

Transformation T_4 is similar to T_2 in that once the strain data is available, the step to obtain the damage is based largely on test and

analysis. The T_5 for present cases is more or less trivial and will not be discussed further except to say it is essentially based on test and analysis and is a low error operation.

6.2.2.1.2 Stress Transfer Functions (CA)

The isolation and determination of the transfer of load effects from a reference location to a remote location must be accomplished initially during testing (flight tests, static tests, fatigue tests, damage tolerance tests) of the airplane in question. Data from instrumented tests may be extended and supplemented with analysis (such as the finite element technique) to yield more varied and general solutions. There is little difference in the stress transfer function requirements between the use of various IAT methods. This is especially true if only one IAT activity indicator is used.

Generally, the critical areas of A/F/T airplanes are concentrated in the wing. However, provision must be made for the case when this is not true. The satisfaction of this requirement demands that statistical methods be developed that will relate loads from one location to another using the IAT activity indicator chosen.

Examples of methods that transfer damage from a reference location to remote locations are direct statistical relationships and "iso-exceedance" relationships. The direct statistical relationship involves deriving regression equations that express the strain at remote locations as a function of various airplane response parameters. These response parameters should include the tracking variable. A data bank of observations of these parameters along with the associated strain will be generated during flight test operations or may be derived analytically. These observations may then be regressed upon to obtain expressions for the transfer of strain.

The previously referenced study outlined an Appendix B used the regression equations approach to calculate loads at remote airplane

locations. The equations used for this study (given in Appendix B) were generated with a stepwise multiple regression analysis. The input data was a set of 110 observations of stress with simultaneously occurring airplane response parameters. The values of stress at the eight locations studied were determined by a finite element analysis of the airframe. The analysis was validated by previous test experience.

The iso-exceedance method involves relating variables by virtue of the number of times they exceed certain values. This method was first used during the U.S. Air Force A-7D ASIP. The method provides a statistical relationship between parameters whose peaks do not occur simultaneously or in cases where there is no basis for the existence of a direct functional relationship. An example of an iso-exceedance relationship, taken from the A-7D study, is shown in Figure 6-6. Here the stress in the airplane's horizontal tail is related to the vertical load factor at the center of gravity. There is, or can be, an influence between the tail load and the load factor, but there is no direct relationship available as the peaks of the two parameters occur at different times. However, a relation is established if the data is observed on an "equal exceedance" or iso-exceedance basis. That is, the stress at a certain level occurs with the same frequency as a selected load factor level. The data can be cross-plotted to reveal a relatively simple empirical relationship. This relationship was established using flight data points, not analysis.

The basic difficulty in transferring damage from a reference location to remote locations is not with the statistical method chosen. The basic difficulty may be whether damage can be transferred in a reliable, repeatable, and reasonably accurate manner. A short study on this problem is also given in Appendix B. It is seen that damage for locations near the wing (of the A-7D anyway) tracks well with the damage at the reference. Locations in the

fuselage do not do so well. Damage at the tails show no correlation with the reference damage.

The solution to this situation lies in one of two choices: overdesign so that there are no critical non-transferrable locations, or accept the conservative penalties required by having a large error in the transfer relationship.

Careful analysis of each individual airplane case is required in the evaluation of damage transfer.

6.2.2.1.3 Crack Growth Simulation (CA)

Based on the studies conducted in this program, the recommended method for using CA data to determine effective crack growth (or length) is to express the crack length (and equivalent damage state) as a direct function of the number of occurrences of the specified n_2 levels. This method is seen to be relatively accurate when compared to more involved methods.

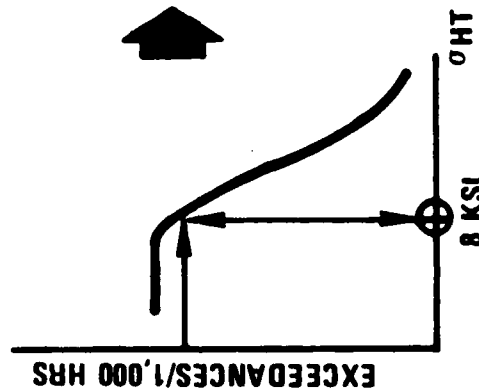
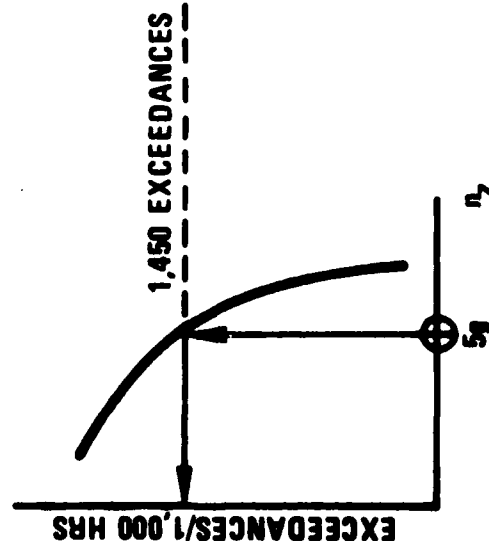
This method entails expressing the damage index as a function of the number of occurrences of the load factor using the methods of stepwise multiple regression. The example to be demonstrated is based on the A-7D. Figure 6-7 is crack growth test data generated during the A-7D ASIP effort. Shown is the response of wing station 32.2 (the reference location for A-7D IAT) when exposed to seven different usage spectra (the "modified baseline" was not used). The spectra used were actual usages from the noted Air Force bases: McEntire, Buckley, Davis-Monthan, and Kirtland. Also used were the actual history of A-7D tail number 701003, the usage of the airplanes in the Pennsylvania Air National Guard force, and the composite of all these spectra (labeled "composite"). The spectrum variable was the output of the counting accelerometer. An average n_2 -to-stress relationship for wing station 32.2 was used in the testing.

A crack length of 1.2 inches is defined as the critical value, and this

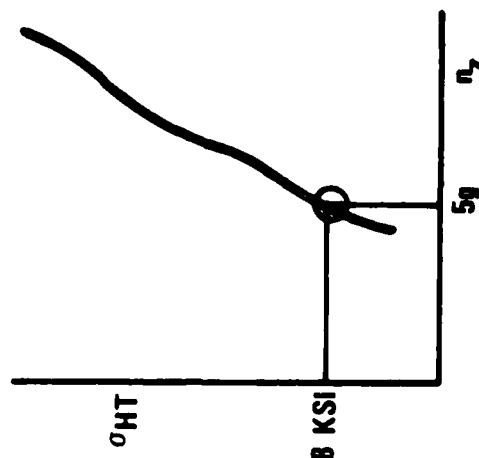
RELATING HT AND VT STRESS SPECTRA TO n_z SPECTRA

EXAMPLE:

PLOT n_z AND STRESS SPECTRA FOR COMPOSITE DATA:



PLOT n_z vs STRESS FOR
EQUAL VALUES OF EXCEEDANCES:



VERIFY RELATIONSHIP
FOR NINE INSTRUMENTED
AIRCRAFT

RELATE COUNTING
ACCELEROMETER DATA
TO HT STRESS COUNTS:

n_z	$\frac{\sigma_{HT}}{8.1 \text{ KSI}}$
5	8.1 KSI
6	12.9
7	17.6
8	22.3

CURVE FIT DATA TO DERIVE
EQUATION WHICH STATISTICALLY
PREDICTS THE STRESS VALUE
WHICH IS EXCEEDED THE SAME
NUMBER OF TIMES AS A KNOWN
VALUE OF n_z :

$$\sigma_{HT} = -15,519 + 4,732 n_z$$

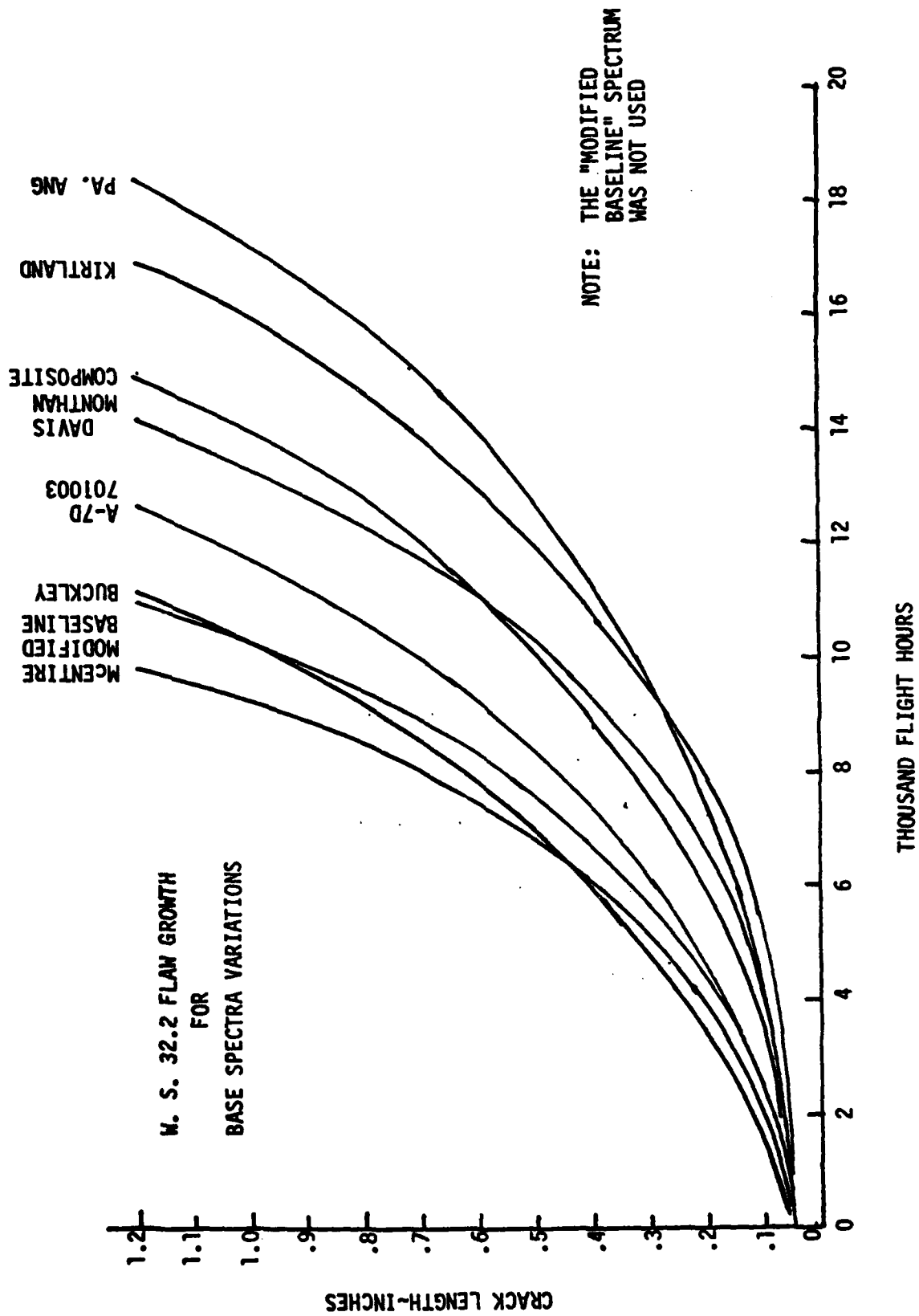


FIGURE 6-7

length corresponds to the maximum allowed damage index. Each of the spectra of Figure 6-7 is characterized by strains (due to the n_z occurrences) of certain magnitudes per unit of flight time. If this data is regressed in a stepwise, multiple fashion, the following equation is produced (see Appendix A):

$$DI = 0.000068869E_5 + 0.000020442E_6 + 0.000071707T + .0042$$

where E_5 and E_6 are the occurrences of 5 and 6 g's, respectively, and T is airplane flight time. This equation will provide an instantaneous damage index upon the increment of any of the independent variables. This approach for expressing the DI as a direct function of the CA data has also been demonstrated using F-4 data as shown in Appendix A.

The above recommended method for expressing the DI as a direct function of the vertical acceleration occurrences is not intended to exclude any of the methods given in the Task I report. A principal strength of the linear polynomial is its simplicity. This capability of being able to express the damage so straightforwardly may allow the application of a microprocessor to the IAT function. While the computations involved in determining a damage using any present method is easily within present computer technology, the simpler the algorithm, the more miniaturized such a device can be made.

In summary, the crack growth technique presented here for the CA is recommended as an improvement, although other methods will undoubtedly give satisfactory answers. The CA method is considered as a baseline.

6.2.2.1.4 Counting Accelerometer Costs

The cost discussion for the counting accelerometer (and other methods to be discussed) will be addressed by itemizing some common cost elements and then giving estimates for the cost of a system referenced to the A-7D airplane. The cost elements for the counting accelerometer method are:

Non-Recurring

- o Cost of transducer and indicator
- o Cost of instrument installation
- o Cost of analytical/test method development

Recurring

- o Data acquisition cost
- o Data processing cost
- o Instrument maintenance cost

Cost items such as the impact of the IAT devices on the airplane design and weight will not be addressed separately. There is some cost effect of these considerations for any method used, and it will be assumed that this effect is invariant with method. The costs of equipment maintenance will not be addressed quantitatively here.

The counting accelerometer cost reference data is developed on the actual installation costs of the devices for the A-7D airplane, cost data for GFE provided by Naval Air Systems Command and estimates of the cost of the remaining elements for which data was available. The devices installed in the A-7D airplane on the production line cost the government \$4,591 in 1979 dollars. This CA installation consists of the MS 25448-1 indicator and the MS2544-1 transducer. Also, the contractor collects a fee of \$100 for each installation: this gives a total cost of \$4,691 per airplane.

Assumptions made in estimating the costs of the CA (and the other methods discussed below) are a fleet of 500 airplanes flying 20 hours a month with each having a life of 15 years. It was further assumed that the CA were read once each month and processed once each quarter. Government labor was assumed to be \$30 an hour. Details of the cost calculations are:

Non-Recurring Costs

Instruments (no spares)

(500 airplanes) (\$4691) = \$2,345,000

Method Development = 500,000

Recurring Costs

Data Acquisition

(500 airplanes) (180 months) (1/4 hour labor, \$7.50)

= 675,000

Data Processing

(500 airplanes) (60 quarters) (\$10 computer time plus 3/4
hour labor, \$22.50)

= 975,000

TOTAL = \$4,495,000

When this total cost is divided by the total flight time for the 15-year period, (500 airplanes) (20 hours/month) (180 months) = 1,800,000 hours, a cost of \$2.50 per flight hour is given. A similar, independent cost analysis by the Air Force (reported in Reference 3) gave a cost of \$2.45 per flight hour.

6.2.2.1.5 Counting Accelerometer Accuracy

Data permitting the assessment of accuracy of IAT methods in terms of actual aircraft fatigue life is difficult to obtain. For the study of the CA given here, the accuracy of damage prediction is referenced to laboratory test results. In particular, the reference data is that from the A-7D ASIP laboratory coupon tests described by Figure 6-7.

The accuracy data is developed in two different ways. First, the experimental DI equation developed from the data of Figure 6-7 was applied to three intervals of each of the constituent usages. Used were low airplane flight time, medium airplane flight time, and high flight time. The data of Table 6.1 summarizes this error data. It should be mentioned here that an

equation for the DI (using the stepwise multiple regression analysis) which use the exceedances of 7g and 8g CA counts was also generated. This equation had two negative coefficients that could cause nonsensical DI values for some usages. This eventually was judged undesirable, and this form of the equation was dropped, even though the errors were smaller than the ones given in Table 6.1.

The second way the error analysis of the CA DI equation was assessed was by creating seven (the modified baseline spectrum was not used in the analysis) different DI equations were composed of six of the seven spectra; a spectrum was alternately omitted. This method then allowed the equation to be checked with usage spectra that were not used in the creation of the respective equation. Table 6.2 summarizes the error data for this case. The variances are somewhat larger than those of Table 6.1. The average error of the 21 points given in Table 6.2 is approximately twice as large as for the data of Table 6.1; 6.1% versus 3.1%. However, it is judged that an average error of 6.1% is not prohibitive for this kind of prediction.

Experience using the F-4 airplane damage data (of Appendix A) increases the confidence in the accuracy that is available using the CA.

6.2.2.2 Mechanical Strain Recorder (MSR)

The advance realized in going from the use of an IAT activity indicator such as the counting accelerometer to one such as the MSR has to be judged significant. The theoretical significance of this move that "effects data" is being used to track damage instead of "causal data." That is, the loads induced in the airframe are caused by pulling vertical load factors; the effects of these maneuvers are structural strains, the near-fundamental damage descriptor. Strain is termed the near-fundamental damage descriptor, because in the absence of actual crack length, a strain history is the next best quantity for predicting damage. The relationship between strain and crack

TABLE 6.1

COMPARISON OF CA DAMAGE INDEX EQUATION WITH TEST

Spectrum	E5	E6	Time a = 1.2 in.	Error - DI EQN and Test		
				Low Time (%)	Middle Time (%)	High Time (%)
McEntire	18,903	4,223	9,884	0.2	5.6	5.6
Buckley	21,728	3,292	11,333	1.1	1.8	2.6
Airplane 701003	20,172	4,624	12,713	9.9	7.0	6.6
Davis-Monthan	18,853	3,408	14,259	0.1	0.7	0.9
Composite	21,002	3,094	14,945	4.2	4.0	3.4
Kirtland	19,795	2,298	17,015	1.7	0.3	0.2
Pennsylvania Air Natl Guard	15,247	2,872	18,558	5.0	2.4	2.6

$$DI = .004 + .0000689E_5 + .000204E_6 + .0000717 \text{ (TIME)}$$

propagation response has been established by test.

The realization of the need for direct strain data is not new. A mechanism that delivers the strain record for airplane application is relatively new. Although the MSR is far from being an optimum device for furnishing strain, its significance lies in the fact that a first step has been taken in pursuit of effects data tracking.

The MSR will be discussed and evaluated not only on a basis relative to the baseline CA method, but also on its own absolute merits.

6.2.2.2.1 Advantages and Limitations (MSR)

The singular advantage of the MSR over the baseline CA system is the absence of the T_1 transformation. To achieve this advantage it must be assumed that the MSR is installed on an airplane such that it accurately and directly records the strain experienced by the location in question. It is also assumed that damage is calculated from strain exceedance data. The other MSR transformations of Figure 6-5 are seen to be characterized exactly as in the CA case.

The disadvantages and liabilities of the MSR are numerous and are principally due to its mechanical nature. Among these are: (1) the requirements for periodic change out of the recorder element; (2) the special data processing requirements of reading the metallic tape by the digital transcribing unit (DTU); (3) the relatively low level of automation of the DTU operation; (4) the physical size (and other features) of the MSR that restricts the structural components at which it can be located; and (5) the need for adjustments and fine tuning of the device to ensure proper operation.

Aside from the cost and handling disadvantages mentioned in (1) and (5) above, it is assumed that the periodic changing of recorder tape based on a capacity limitation will cause loss of data. The liabilities of (2) and (3) above are due to the fact that the tape reading operation is a semi-manual

operation accomplished on a specially designed and built machine that has its own maintenance costs. Use of the MSR requires the bolting or bonding of an eight-inch long instrument to the structure. It is clear that maximum benefit of the device may not always be realized, since it cannot be located arbitrarily. That is, the strength of the MSR is its ability to read strain directly; if the instrument cannot be located at a target critical location (say only close), then an equivalent T_1 may be required.

In summary, the MSR applications programs have had their break-in-problems (see Reference 11 and 12). The device is delicate and sensitive to rigging adjustments, and its return of good data has been below expectations. Its mechanical nature limits its desirability as an IAT method. Appendix C discusses results of an MSR program conducted on the A-7D airplane.

6.2.2.2.2 Stress Transfer Functions (MSR)

The methods of transferring load effects from a reference location to remote locations are not peculiar to the MSR activity indicators. The discussion of 6.2.2.1.2 is assumed to apply equally to the MSR if only one instrument is used. If multiple instruments were to be used for IAT, at least theoretically, the availability of data at several well-placed locations would allow the transfer of stress with much greater accuracy. If a correlation scheme were to be available there is little doubt that for a particular airplane configured with, say three MSR's, interpolation or extrapolation techniques could be developed that would allow accurate mapping of the airplane's structural load experience.

However, the practical drawbacks of such an IAT configuration would be great. It is anticipated that only a small percentage of good data would actually be produced. The advantage of having three instruments is the provision of simultaneous data. If one or more devices are malfunctioning for a period of time, the usefulness of the remaining good data is greatly

TABLE 6.2

COMPARISON OF DI EQN RESULTS FOR ALTERNATELY MISSING SPECTRA

Missing Spectrum	Error - DI EQN and Test		
	Low Time (%)	Middle Time (%)	High Time (%)
McEntire	6	10.5	10.6
Buckley	2.9	4.8	5.0
Airplane 701003	10.5	12.0	11.8
Davis-Monthan	0.6	0.8	1.1
Composite	3.8	4.2	4.6
Kirtland	1.8	0.7	0.7
Pennsylvania Air Natl Guard	13.2	11.1	11.7

diminished. In short, it appears that an installation of multiple MSR's would not be practical for IAT application. The cost and logistics problems would not allow such an installation to be competitive with other IAT methods.

6.2.2.2.3 Crack Growth Simulation (MSR)

Because of the high cost of predicting crack growth on a sequenced cycle-by-cycle analysis, it is assumed and recommended that damage predictions with MSR's be made based on strain exceedance or occurrence data. The original IAT method envisioned for the F-16 airplane planned a cycle-by-cycle crack growth analysis. However, the method was later revised to use occurrence data. The discussion here agrees with the F-16 decision that the cycle-by-cycle prediction is not cost effective.

Crack growth simulation using strain exceedance data can be implemented successfully in several ways. For example, the F-16 method reported in the Task I report is satisfactory. Another could be the method discussed for the CA - the expressing of the DI as a linear function of the exceedances of specific levels of strain. This method actually reduces to equations having the exact form as those for the CA discussed in paragraph 6.2.2.1.3.

The data of Table 6.3 was used to simulate A-7D MSR data. This data is from the A-7D ASIP flight test and relates vertical load factor to stress. The construction of a damage algorithm from this data resulted in the exact equation of paragraph 6.2.2.1.3. This is because the independent variables are the number exceedances of specified load indexes, and the actual engineering units are irrelevant to the regression analysis.

6.2.2.2.4 MSR Costs

The cost study presented here is based on the MSR instrument presently being used for the F-16 airplane IAT program and the A-7D L/ESS program. Both these program are embryonic with respect to an MSR IAT system and are experiencing start-up difficulties. The cost discussion here assumes a smooth production operation.

TABLE 6.3

A-7D TEST SPECTRA USED IN CA AND MSR ANALYSES

(TEST TIME IS TIME TO REACH A CRACK
LENGTH OF 1.2 INCHES AT WS 32)

Spectrum	E ₃ - 3g (10,900 PSI)	E ₄ - 4g (14,400 PSI)	E ₅ - 5g (17,900 PSI)	E ₆ - 6g (21,300 PSI)	E ₇ - 7g (24,800 PSI)	E ₈ - 8g (28,300 PSI)	Test Time (Hours)
McEntire	123,550	50,408	18,903	4,223	387	11	9,884
Buckley	132,322	56,042	21,728	3,292	121	10	11,133
Airplane 701003	145,576	59,838	20,172	4,624	375	31	12,713
Davis- Monahan	147,641	63,281	18,853	3,408	338	24	14,259
Composite	164,594	67,208	21,002	3,094	262	24	14,945
Kirtland	188,713	75,133	19,795	2,298	121	13	17,015
Pennsyl- vania Air Natl Guard	176,301	66,809	15,247	2,872	205	0	18,558

The cost elements of an MSR IAT method are:

Non-Recurring Costs:

- o Cost of instruments
- o Cost of covers
- o Cost of attachment mechanism
- o Cost of installation
- o Cost of tape reader (DTU)
- o Method development

Recurring Costs:

- o Cost of cassettes
- o Cost of changing cassettes
- o Cost of data reading
- o Cost of data processing
- o Cost of equipment maintenance

The MSR quantitative costs are developed based on the estimated costs for the A-7D program and the same assumptions made for the CA. The hardware component costs given below are 1979 actuals derived from vendor invoices. The method development is nominally priced at \$.5M to reflect the cost of testing several structural specimens to acquire crack growth characteristics. This cost is used for the method development for all devices.

The cost of the cassettes and changing the cassettes is based on a cassette being able to contain the flight activity of one calendar quarter. The cassette tape digitizing operation on the DTU is assumed to be \$22.50 per tape. The data processing costs are given at \$10 per tape. This is based on the assumption that a damage equation is a simple algorithm discussed earlier. An itemization of the costs are:

Non-Recurring:

Instruments	(500 airplanes)(\$1,379/MSR)	= \$ 689,500
Covers	(500 airplanes)(\$50/cover)	25,000
Attach Bolts	(500 airplanes)(\$40/bolt)	20,000
Installation	(500 airplanes)(\$60/installation)	30,000
Dio	(5 units)(\$100,000/unit)	500,000
Method Development		<u>500,000</u>
		\$1,764,500

Recurring:

Cassettes	(500 A/P)(60 qtrs)(\$80/cassette)	\$2,400,000
Change Cassettes	(500 A/P)(60 qtrs)(\$15/change)	450,000
Data Reading	(500 A/P)(60 qtrs)(\$22.50/cassette)	675,000
Data Processing	(500 A/P)(60 qtrs)(\$10 computer time)	<u>300,000</u>
		\$3,825,000
	TOTAL	\$5,589,500

When divided by the assumed 1,800,000 flight hours for the life of the total force, a cost of \$3.11 per flight hour results. For comparison, the study of Reference 3 gave \$1.25 per flight hour and the study of Reference 4 gave \$1.42 per flight hour. A principal contributor to the differences in cost estimates is the updating of the cost of the instruments and data processing.

6.2.2.2.5 MSR Accuracy

The accuracy of a MSR method using an algorithm written in terms of exceedances of strain levels is almost guaranteed to be more accurate than a similar CA method. This follows from the fact that since strains are being read directly, there is no error in T_1 . The MSR lends itself to

cycle-by-cycle prediction of crack growth, but the cost is prohibitive as discussed above. It is judged that no great loss is sustained by not analyzing the structure of A/F/T aircraft with cycle-by-cycle methods.

As another check on the accuracy of an MSR method, several checks were made using the F-16 airplane tracking method. The several checks made were done by applying simulated A-7D MSR data to the F-16 method. Figure 6-8 presents data used in one of these checks. It was assumed that the upper and lower spectra were the closest spectra bounding the simulated A-7D usage. (The F-16 uses a total of five spectra for possible interpolations or extrapolations.) The data of Figure 6-8 represent stress spectra of the A-7D wing station 32.2 location. Analytical crack growth data was available for all three of the displayed spectra. Comparing the F-16 method results for predicting the crack growth response with the time (analytical) results gave a difference of 2.5% at a high crack length (1.0 inch) and a difference of 4% at a low crack length (0.2 inch).

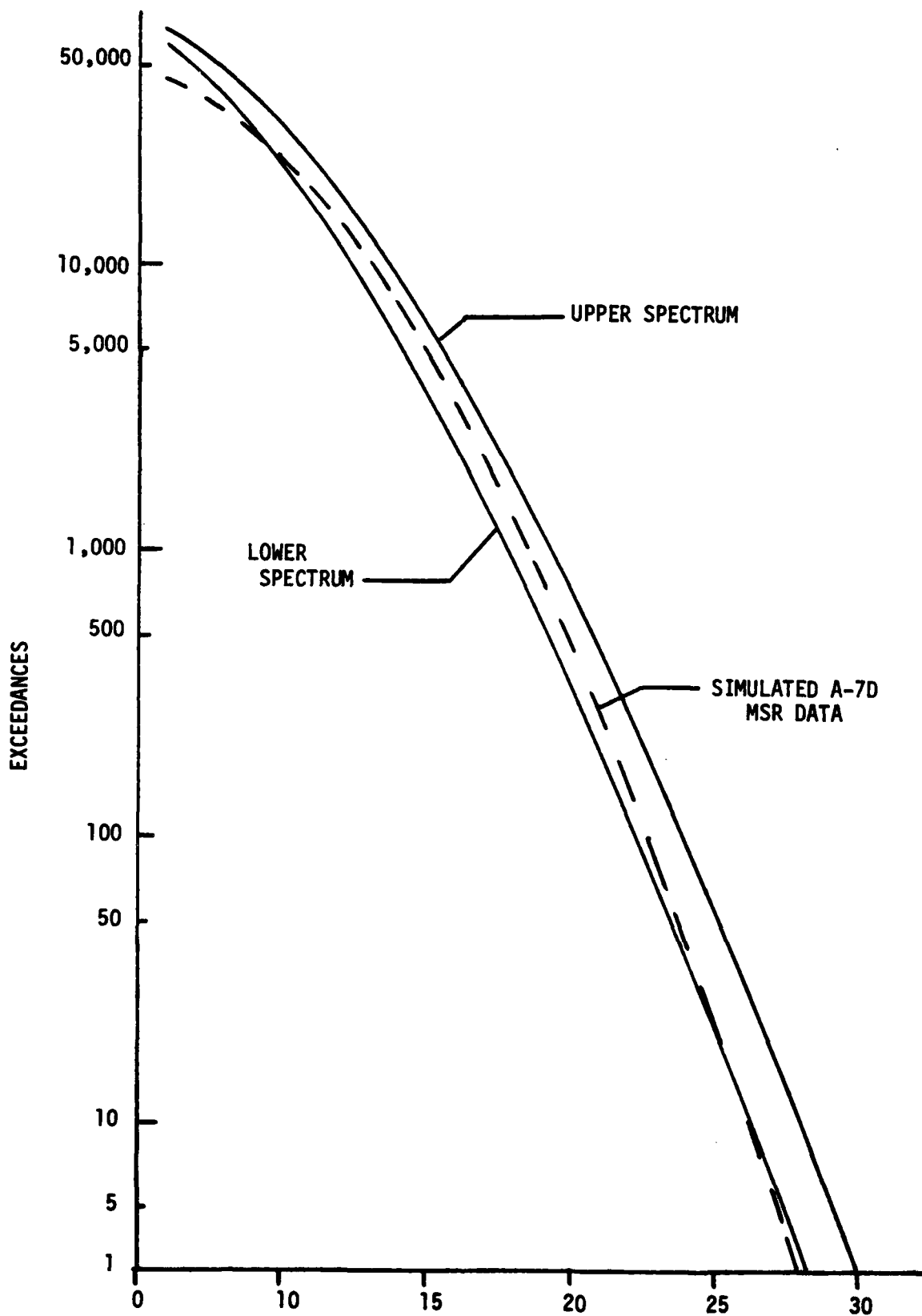
The average error for all the checks made was 4%. This is considered excellent accuracy.

6.2.2.3 Microprocessor (MP) Based Systems

6.2.2.3.1 Advantages and Limitations (MP)

A MP based IAT method is considered here to be the obvious selection for future aircraft. The advances made recently in the field of electronic micro-miniaturization demand an application of this technology to the relatively simple task of structural tracking of airplanes. There are several experimental systems under evaluation by not only the Air Force, but also the Navy. These seem to have been developed for some particular purpose and likely would not presently perform well for the general application to IAT. Industry sources state that MP-based IAT will have application only for future airplanes. Reasons quoted are that the combined development and retrofit

SPECTRA USED FOR MSR ACCURACY STUDY



STRESS-THOUSANDS OF PSI
FIGURE 6-8

costs are prohibitive. This has some basis in that the Air force does not have the resources to abandon thousands of \$5000 counting accelerometers and replace them with \$5000 microprocessors. This is particularly sensible in light of the fact that the CA are doing an adequate job. The discussion here will not disagree with the MP industry position that the MP is more likely to be used on future systems. The MP method will be discussed and evaluated on its own merits as an IAT system. It will be further assumed that the MP is developed and available.

The MP method discussed here is a hypothesized procedure insofar as application to Air Force IAT is concerned. However, it is well within current technology, and the only unknown is the development costs. The advantages are higher accuracy than a baseline CA method with greatly streamlined data processing.

Hypothesized Microprocessor Description. The key to the method for IAT application is the availability of a one-channel microprocessor which has the ability to:

1. Convert the signal from an electrical strain gage into exceedance data of some specified stress levels. To perform this function, the MP must be programmable to test the slope of the signal, apply the desired magnitude criteria, scale the value, and edit the data.
2. Store several pieces of data. The storage requirements probably will be on the order of 10 numbers or less. It has been shown in one case (the A-7D) that as few as two load level occurrences are adequate for the calculation of an accurate damage index. The storage registers will provide data represented by Figure 6-9.
3. Perform arithmetic calculations on exceedance data. It is envisioned that one relatively simple polynomial or logarithmic function can be generated that will define the DI. The method

for doing this has been described in Section 6.2.2.1.

4. Provide a visual display of data upon interrogation. This display can possibly be similar to the LED or LCD presentation of modern hand-held calculators. The readout or display could be conveniently located to enhance the probability of getting regular, accurate readings.
5. Perform internal auditing of the instrumentation and data signal quality. This ability is mandatory to suppress the use of faulty data and to provide a basis for gap-filling.
6. Monitor airplane cumulative flight time (if time is a variable in the DI definition).

This method will be referred to here as a microprocessor/strain counter (MP/SC) in subsequent discussions. The device is actually a strain recorder used as a strain counter. The method entails calculating a damage index from the strain exceedance data of Figure 6-7 by the methods of 6.2.2.1. It is assumed here that the system of interest is a one-channel system. Industry sources state that the projected cost of a MP varies with the number of channels of data according to Figure 6-10. This doubling of cost when going from one to two channels is due to additional signal conditioning requirements.

The clear advantage of the MP/SC is that the device is electronic

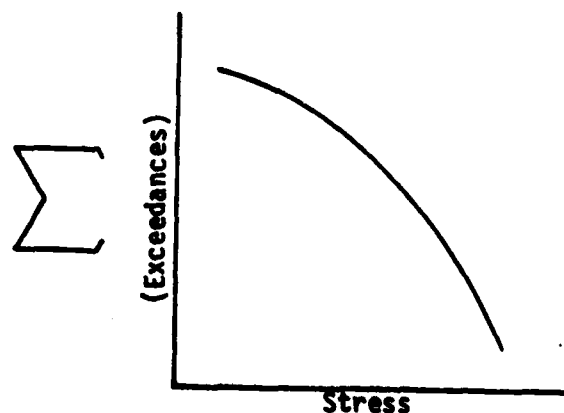


Figure 6-9 MP Stress Accumulation Example

VARIATION OF MP COST WITH DATA CHANNELS

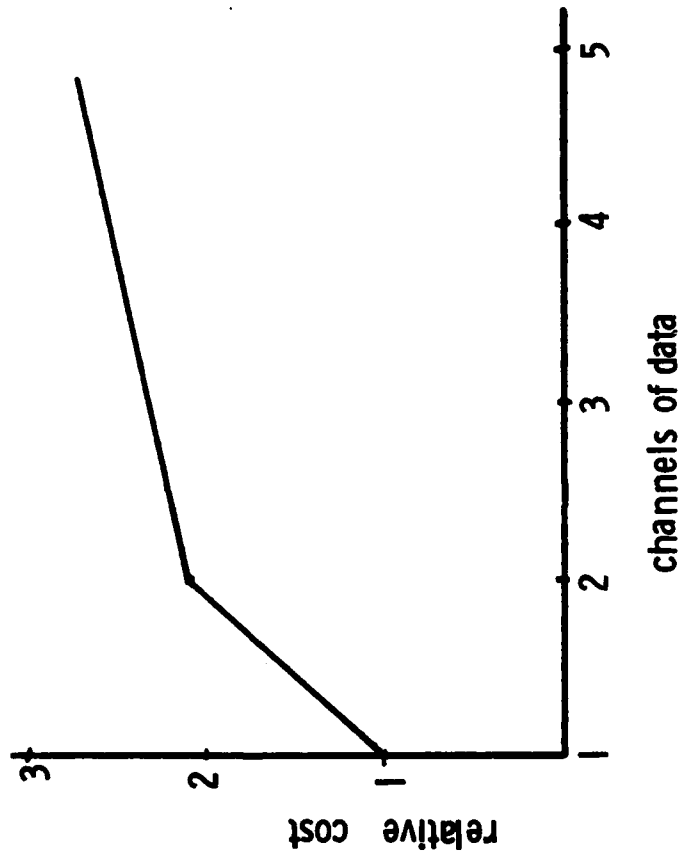


FIGURE 6-10

versus mechanical. A highly likely advantage of the MP/SC will be the calculation of a DI "on the fly". Interrogation of the device could be the displaying of the DI and the exceedances that were used in its calculation and loading this data onto a form for submission to the structural management organization. The structural management function would then go through a series of checks and comparisons with past data to validate the calculated DI and the accumulated exceedance data.

Supporting advantages of the MP/SC system are the reliability and automation features. Liabilities are associated with the use of strain gages as the transducers - especially if the gage is located at an inaccessible location. There are various opinions on this, but one instrumentation industry source gave the useful life of a strain gage as an 85% chance of lasting ten years. A strain gage is defined as a primary and back-up. There is also an increase in error from the gages as the temperature rises. This increase is on the order of an additional 2% error.

As may be seen below, the hypothesized MP/SC IAT system is determined to be superior to other methods for A/F/T IAT.

6.2.2.3.2 Stress Transfer Functions (MP)

The problem of transferring loads from a reference location to others in the airplane will be no different using a one-channel MP system than that of the CA. The prediction of remote load effects will remain in the domain of statistics.

6.2.2.3.3 Crack Growth Simulation (MP)

The crack growth or damage index may be derived from the MP strain exceedance data in the same ways as those for the MSR. In fact, the MP/SC method hypothesized here may be considered to be an electronic strain recorder (or counter) instead of a mechanical strain recorder (or counter). This will allow CA or MSR methods for simulation of crack growth to apply.

6.2.2.3.4 MP Costs

Definitive cost data for the hypothesized MP/SC is impossible to obtain. This is because potential vendors will not release formal, official estimates for these costs without detailed specifications. The construction of detailed specifications are beyond the scope of this effort. However, the two vendors that would supply informal estimates projected costs that would be directly competitive with the CA. As mentioned above, these costs do not include hardware development expenses. Therefore, the cost of data acquisition and processing into DI will be quoted at \$2.50 per flight hour, the price of the CA quoted above.

6.2.2.3.5 MP Accuracy

The accuracy of a MP/SC method is judged as better than that of the MSR. Better accuracy is possible principally because of a projected higher return of good data with the electronic system versus the mechanical system. For a given equal amount of good data, the electronic method would be superior because of the slight error inherent in the metal tape reading. The DTU's reading of the traces is imperfect in that there is a trace thickness to contend with. The overall accuracy is given to be less than 5% error. These statements are based on the accuracy studies of the CA and MSR. Similar principles are involved in the calculation of the DI.

6.2.2.4 Crack Growth Gage (CGG)

The Air Force has been conducting extensive research into the application of the CGG concept as an IAT tool since 1975. As of this writing, the technique has not been shown to satisfy the repeatability, endurance, and reliability demands of a viable IAT method. However, since the device holds such promise as an IAT tool, research into solving its known shortcomings is continuing.

The following discussion will address the CGG from two points of view. First, the problems presently being experienced will be presented and

evaluated; secondly, the overall evaluation of IAT methods of paragraph 6.2.3 will assume that the device has had its major problems solved. Without this assumption, there would be no need to evaluate the method in light of the other operational or state-of-the-art methods.

6.2.2.4.1 Advantages and Limitations (CGG)

The crack growth gage is a small precracked element mounted on an aircraft structure that is intended to experience the same displacement-time-environmental history as the monitored structure. The underlying concept behind the gage is that the crack in the gage will grow in a manner directly and repeatably relatable to assumed cracks in the structure. In this sense, the CGG may be likened to an analog computer which senses the load history, environment, and time effects, determines its effects on crack growth, and responds with a measurable output. This output is a change in crack length. A transfer function is possibly required between the crack growth response of the gage and that of the monitored structure.

The principal theoretical advantage of the CGG is its simplicity of operating principle. A suitable structural location equipped with a gage will display its damage state explicitly in terms of the fundamental IAT parameter-crack length. Limitations associated with this advantage are the problems with isolating "suitable" structure. The structure must be accessible for inspections of the CGG. Also, for maximum benefit of the gage, the structure should be critical.

In practice, there are several inter-related problems to be solved before the gage concept can become operational. The first of these is gage design. The final gage configuration must be capable of exhibiting measurable crack growth behavior in the interval between inspections. The size of the gage must necessarily be small in order to avoid high stress gradients and physical interference problems with the critical structure. Provisions must also be made in the design to preclude elastic stability (buckling) problems

with the gage upon the experiencing of compressive loadings.

Gage design must also provide for a suitable attachment method. To date, most experimental gages have been bonded to the parent structure with either hot or cold bond adhesives. The hot bond adhesives are more attractive because of their durability; however, obtaining the proper bond temperatures for adequate curing has been a problem because of the large heat sink characteristics of the critical structure and the desire not to degrade material properties with the elevated temperatures. The attachment method requires consistent load transfer characteristics that will be invariant over the lifetime of the gage. The attachment must also retain its integrity for the purpose of reducing in-service maintenance. That is, the superposition of crack lengths from more than one gage has not been established. It is desirable that one gage last the entire lifetime of the structure.

Another problem to be resolved with the CGG is the calibration and reading of its output. A method is required that facilitates easy, accurate reading in the field by operational personnel. Several methods have been investigated including microscopes, macro camera set-ups, fax film, and crack wire (electrical potential methods). The fax film method appears to be the most promising, but requires further development. The key to gage reading is accuracy and simplicity.

A last major problem to be overcome is the protection of the gage from adverse airplane operating environment. Some type of protective coating will probably be necessary, but this cannot be at the expense of the reading requirements. The gage must be placed so it is not exposed to any extremes of thermal or chemical environment that would affect the gage differently than the parent structure or that would cause a degrading of the reading.

The above noted problems are more or less mechanical in nature and are expected to be solved by additional development efforts. The non-mechanical problems are theoretical in nature and will require in-depth analysis. The

principal problem is the question of a transfer function between the gage output and the parent structure crack state. This problem has been the focus of considerable attention, but to date no viable transfer function has been demonstrated. Early test results for constant amplitude cycling show considerable promise for the transfer function developed by Grandt et al reported in Reference 5. However, when this transfer function was used to describe variable amplitude flight-by-flight behavior, general applicability was not demonstrated. Test results reported in References 4 and 6 indicate that the transfer function depends on the content of the load spectra. That is, the function is not single valued. Knowledge of the content of the spectra is tantamount to knowing part of the answer beforehand.

The problem of the transfer function dependence upon load history seems to be a result of retardation from different spectra affecting the thicker critical structure differently than that of the thinner CGG structure. Gray and Grandt (Reference 7) have suggested an approach which provides a solution for the transfer function-dependence problem. The solution to this problem is mandatory to the success of the CGG.

One final liability of the CGG is its inability to record any historical data describing the airplane usage. Only the effects are present; no information as to the cause of the crack will be available. This liability appears to be non-fatal as far as the usefulness of a fully developed CGG is concerned, however.

6.2.2.4.2 Stress Transfer Functions (CGG)

The determination of methods to transfer damage from a reference location to other critical locations in the structure will fall in the domain of flight test and statistics. There appear to be no unique problems in transferring damage due only to the use of the CGG.

6.2.2.4.3 Crack Growth Simulation (CGG)

With a fully developed crack growth gage, there will be no simulation

to the crack growth activity. It is expected that the crack growth in the gage will reflect the growth of the parent structure.

6.2.2.4.4 CGG Costs

The CGG has the potential of being the least expensive IAT method discussed here. The cost elements for the CGG are:

Non-Recurring

- o Cost of instruments
- o Cost of installation
- o Method development

Recurring:

- o Data acquisition
- o Data processing

Estimates for reading the gages each quarter are:

Non-Recurring:

Instruments	(500 A/P)(\$500)	= \$ 250,000
Installation	(500 A/P)(\$550/airplane)	= 275,000
Method Development		= <u>500,000</u>
		\$1,025,000

Recurring:

Data Acquisition	(500 A/P)(60 qtrs)(\$10/reading)	= 300,000
Data Processing	(500 A/P)(60 qtrs)(\$10/reading)	= 300,000
		<u>\$ 600,000</u>
	TOTAL	\$1,625,000

These costs result in a net cost per flight hour of \$0.90. Reference 3 gives an estimated cost of \$0.56 per flight hour.

6.2.2.4.5 CGG Accuracy

The CGG gets the highest accuracy score of any IAT method graded here. This high grade is due to the assumed absence of T_1 and T_2 of Figure 6-3.

It is believed that a properly and fully developed method will have the capability to display the actual (or near-actual) crack length of the monitored structure. The T_3 , T_4 , T_5 transformations are further assumed to be identical in nature to those of the CA, MSR, and MP/SC. However, if multiple gages were to be used, T_3 could be eliminated. This would increase the accuracy.

6.2.3 Comparison of Monitoring Techniques

This section will summarize the discussions presented above for the subject IAT methods. The cost and accuracy comparisons are basically deterministic once the assumptions are established. The "implementation" considerations are likely to be viewed as subjective discussions because there is disagreement in the IAT community as to the relative merits of the methods. Substantiation is presented for all conclusions.

Table 6.4 summarizes the cost and accuracy data for the methods discussed. The MSR, MP, and CGG are all rated as having an accuracy of more than 95%. The counting accelerometer is given an error bound of 10%. The accuracy estimates are for comparisons of prediction technique results and test data. This is not necessarily the same as an error in actual airplane fatigue life projections. The relationships between the errors in remaining fatigue life for the methods are expected to be the same as the errors of the test data comparisons.

The degraded accuracy of the counting accelerometer is due to the nature of the T_1 operation. There are two substantiations of the conclusion of reduced CA accuracy. First, the study of Appendix B indicates dramatic effects of flight parameters to which the CA is blind. This study was done to establish trends and should not be construed as being a reflection of the CA capabilities as a general IAT method. The reason is that the mission parameters were changed substantially in the study and it must be assumed that a structural manager will be able to make adjustments in his damage calculations to mitigate some of these effects.

Second, preliminary results from the A-7D MSR program indicate differences in damage rates of up to 30% between MSR and CA predictions. The reason for this difference is that the airplane sometimes experiences an oscillation in vertical acceleration at or near a peak. The lower bound for the excursion of this oscillation is less than the reset value chosen for the

TABLE 6.4
SUMMARY OF ESTIMATED IAT COSTS AND ACCURACY

METHOD	TOTAL PROGRAM COST	COST PER FLIGHT HOUR	ERROR
MSR	\$5,589,500	\$3.11 ¹	< 5%
CA	\$4,495,500	\$2.50 ²	<10%
MP	\$4,495,500	\$2.50 ³	< 5%
CGG	\$1,625,00	\$0.90 ⁴	< 5%

- NOTES: (1) Reference 3 estimated \$1.25; Reference 4 estimated \$1.43 for bomber/ transport
- (2) Reference 3 estimated \$2.45.
- (3) Reference 3 estimated \$1.65; Reference 4 estimated \$2.00.
- (4) Reference 3 estimated \$0.56.

counting accelerometer. For example, if a local acceleration history goes from 1g to a peak of 7g, to a 4.5g valley to a 6g peak and then back to 1g, the CA will not record the oscillation between the 7g peak and the 1g, steady state because the reset value of the CA is 3g. Analysis shows that there is damage due to the unrecorded 4.5g to 6g excursion. The MSR records the entire activity and correspondingly provides the basis for more accurate damage predictions. The net effect of this lapse on the part of the CA is not known because it is not known how often the oscillations occur, etc. Also, a compensating change would be to reprogram the reset value of the CA.

The MP is rated as the easiest method to implement because of its anticipated high reliability, high accuracy, and potential for simplicity. The principal disadvantage is its dependence on possibly inaccessible strain gages. The CA is given an implementation ranking behind the MP because of its simplicity and its status of being well understood and procedurally checked out in the field. These considerations result in a low technical risk situation for acquiring good data. A principal disadvantage of the CA is its lower accuracy rank.

The idealized CGG gage is given an implementation ranking of third because of its high accuracy and capability of reflecting time and environmental capability of effects in addition to providing actual crack growth. A principal disadvantage of the CGG is its inability of being arbitrarily placed.

The MSR is rated last for implementation. The advantages of the MSR are its accuracy and its ability to provide an actual strain history. Principal disadvantages are its mechanical nature, its requirement for periodic change-outs of the cassettes, intermediate data processing steps with special machines (the DTU), and its lack of arbitrary placement.

6.3 IAT SYSTEM IMPLEMENTATION

The ideal IAT system is one that provides complete and accurate

tracking data at a low cost. There is no hope of the Air Force achieving this goal without early planning in the procurement of an airplane weapons system. This planning should be designed to merge the IAT function into the airplane life cycle experiences just as much as routine operations such as refueling are. This planning should further be directed toward simplicity of procedures and simplicity of equipment. Generally, the productivity of an IAT system is inversely proportional to its complexity.

The more complex the IAT operation is, the less likely it is to furnish data. The more complex the IAT operation is, the more pressure and priority must be brought to bear on the squadron level personnel. In other words, a complex system demands higher priority to obtain less data. The following discussion presents the hypothesized implementation of the chosen MP/SC IAT system in a step-by-step manner.

Step 1. The IAT reference location for a new airplane is chosen. This choice is based on the results of full scale laboratory testing, prototype flying, and analysis. The prototype flying is assumed to be done with a highly instrumented airplane. The instrumented locations are expected to be extensive enough that the final choice of an IAT reference is included. The data taken during the flight test phase will be used later in the transfer of damage effort and to support the L/ESS function.

Step 2. Each production airplane is equipped with the microprocessor, wiring, and strain gage. It is assumed that the microprocessor has the capability of providing a visual display of the number of exceedances of the strain levels of interest. The visual readout will be located in the airplane at a convenient and accessible panel.

Step 3. When the airplane is delivered and assigned to an operational command, the procedure for acquiring the IAT data will require the interrogation of the MP unit by a maintenance personnel say, once a month.

The accounting information will consist of:

- o Data
- o Airplane Model and Tail Number
- o Base Code
- o Name and Grade of Person Taking Data

The information taken from the MP unit will be:

- o Flight Time
- o Strain Exceedance Data at the Levels Stored
- o A Notation of any malfunction flags

As mentioned earlier, it is assumed that there will be a need for approximately eight registers required to store the strain exceedance data. The malfunction flags are assumed to be present as a diagnostic aid for both the maintenance personnel and the structural manager. For example, if power to the unit has been interrupted and there is danger of faulty data, a coded flag would alert the user. The data from each airplane would be taken once a month preferably by the same person. This data could be logged onto a ledger listing all airplanes for quick reference as to which ones have been interrogated.

Step 4. The structural manager will process the post card data much the same as ASIMIS now processes the counting accelerometer data for the A-7D airplane. Quarterly summaries for every airplane of a model will be produced. This summary will contain, among other data, the damage index for the airplanes. Inspections are then driven by this DI.

It is envisioned that data loss will be minimized by the assignment of the data-taking duties to specified squadron individuals. If a ledger sheet is not received by the structural manager for a given month, provision could be made for notifying the responsible party's superior of this failure. An occasional missing record will not seriously impact the IAT, since the data is cumulative.

With the increased reliability of an electronic IAT method and simple reporting procedures, the yield of good data would be in excess of 90%.

7.0 LOADS/ENVIRONMENT SPECTRA SURVEY (L/ESS) METHODS

This section evaluates the L/ESS methods presently in use by the Air Force and recommends improvements where applicable. The methods addressed are the multiple channel recorders (MCR) such as the MXU-553, the velocity, load factor, altitude (VGH) recorders, a system based on use of microprocessors, and a simple system using MSR's. These methods will be evaluated and ranked according to relative cost, accuracy, ease of implementations, and overall effectiveness.

7.1 L/ESS REQUIREMENTS

MIL-STD-1530A specifies that the objective of a L/ESS program is to define the actual stress spectra that critical areas of an airframe experience. This history taking of stress data for the critical areas is to be the lesser of three years duration or the period required to take the data equal to one design lifetime. The standard further specifies that the data shall be used to assess the applicability of the design and durability test loads/environment spectra and to develop baseline operational spectra for the airplane model under consideration. The purpose of the operational spectra is to update the durability and damage tolerance analyses. The update of these analyses will drive the redefinition of critical areas, damage rates, and damage limits, as required. The structural manager will be advised of the new definitions and subsequent reprogramming of maintenance actions by way of an updated force structural maintenance plan.

In recognition of the likely cost of such L/ESS programs, the military standard suggests that a force sample of only 10 to 20 percent is adequate for defining the operational spectra. A sample of this size is considered to be statistically adequate for a force consisting of up to several hundred airplanes. It is recommended also that the distribution of the airplane assigned to the L/ESS be made according to the proportion of flying hours. That is, the most active bases, those with the most airplanes, should have a

corresponding proportion of the instrumented airplanes.

7.2 L/ESS METHODS

7.2.1 L/ESS Parameters

While the fundamental parameter of the IAT function is structural crack length, the basic parameters of L/ESS are operational stress (or strain or load) spectra of critical locations. These stress spectra are needed for comparison to the corresponding spectra used for structural design and test. The design spectra originate with the definition of projected usages of the airplane and the subsequent calculation of associated repeated airframe loadings. The airframe is tested under the guidance of MIL-STD-1530A to determine the response of critical locations to these loading spectra. The L/ESS program simply provides the mechanism for determining the actual operational spectra to allow a comparison to the spectra used in the design process. This comparison will reveal any oversights or mistakes in the testing or analysis and faulty assumptions about how the airplane will be flown. Interpretation of the data will either validate or update the mechanism by which the IAT projects damage rates for the entire force.

While MIL-STD 1530A specifies the product of a L/ESS program to be the operational stress spectra of critical points, it also strongly suggests, or assumes (see paragraph 5.4.4), that these spectra will be obtained from time histories of airplane parameters. The use of time histories will be shown to be more expensive and less accurate than the direct recording of critical strain exceedances in a microprocessor based method.

7.2.2 L/ESS Monitoring Techniques

7.2.2.1 Multichannel Recorder (MCR)

7.2.2.1.1 Advantages and Disadvantages

Current use of (non-VGH) MCR for the acquisition of L/ESS data reflects the suggestion of MIL-STD-1530A by recording time histories of airplane response parameters such as angular rates and accelerations, discrete events,

load factors, surface deflections, etc., and, in some cases, strains. This data is time-sliced (to preserve simultaneity) and used to calculate the desired stresses. The calculation of unrecorded airframe stresses is accomplished in two ways. Statistical regression equations relating the desired stresses to the independent recorded variables are derived from flight test and analytical data. Another method is based on the calculation of unit solutions which relate unit parameter values to stresses. The regression equation method is outright statistical. While the unit solution method is based heavily on analysis, it is subject to similar errors as the regression method.

The principal advantages of the MCR method are:

- (1) The time history data base allows the calculation of an arbitrary number of stresses. This could be significant if it is discovered that an unexpected location is critical. The loading history of such a location could be easily recovered from the data.
- (2) The time history data base provides characteristics response parameter spectra data in addition to stress spectra. The Air Force has an interest in acquiring this type data for possible use in future design activities.

The principal disadvantages of MCR's for the L/ESS function are not theoretical, but are practical. These disadvantages are:

- (1) The recorders demand a high level of maintenance because of their reliability shortcomings.
- (2) The recorders require periodic change-out upon reaching a capacity. This activity is subject to oversight and results in lost data.
- (3) Data processing and reduction costs are very high.

Because of the high maintenance burdens associated with MCR equipment, the operational units consider L/ESS airplanes a nuisance and a low return of good data results.

7.2.2.1.2 MCR Costs

The cost data given in the Task I report will be used in concluding that the MCR method is the most expensive L/ESS method in use. The maintenance and logistics costs are high, but are considered indirect by the government. That is, a squadron is given certain fixed resources. The addition of the responsibility associated workload of L/ESS airplanes does not result in an increase in manpower. In an accounting sense, the maintenance and handling of MCR elements is considered free. In practice, the cost of this workload is lost data. The cost discussion will be restricted to that of the data reduction and processing.

Aside from the known high cost of the MCR equipment maintenance, another major cost item is data processing. The F-16 airplane L/ESS program, the first developed under the MIL-STD-1530A direction, was devised as an optimum, ideal function based on the MCR. This program was developed by a highly qualified contractor and applied to a sophisticated state-of-the-art airplane. Features of the effort include using airplane response data that is already available as resource data for L/ESS. Some parameters are made available initially for use by the air data computer; others are taken directly off the airplane instrumentation system. These features provide cheap, high quality data sources.

A major cost item in this system is that of data reduction. Time histories of 22 parameters for 25 flight hours per month for 20% of the F-16 force for several years is an enormous quantity of data. It is understood that the cost of reducing this data has ranged from one hour of computer time per flight hour to one hour of computer time per 15 hour of flight time. This method will obviously produce a complete and accurate loading history for the airplane, but at a high cost. The challenge is to have access to a method that produces accurate results at a substantially reduced cost. The

hypothesized microprocessor based system discussed below is intended to do this.

7.2.2.2 VGH Based System

7.2.2.2.1 Advantages and Disadvantages

The VGH method is considered a suitable L/ESS method for some airplanes only. This restriction follows from the fact that velocity, altitude, and normal load factor are the only available parameters. There are some airplanes (such as the A-7D and F-4) that lend themselves to this method. Critical stresses for these airplanes are concentrated in the wing and may often be calculated satisfactorily from these three parameters.

An experimental structural tracking program is presently being sponsored by the U. S. Navy with the A-7E airplane as the test bed. This program uses the VGH parameters to calculate the damage at the critical points in the wing.

In summary, the principal advantages of the VGH method for some airplanes are:

- (1) The use of the three parameter method allows relatively simple and economical data reduction techniques such as the F-4 table look-up procedure. The VGH parameters lend themselves to methods essentially using exceedance data for damage or spectra determination.
- (2) The method provides historical usage data.

Major disadvantages are:

- (1) The limitation on the applicability of the method to an arbitrary airplane configuration. An airplane with unusual control methods or aeroelastic characteristics may not be suitable for such an incomplete list of L/ESS parameters.
- (2) The reliability of the tape recorder and subsequent maintenance results in a high percentage of bad data. The F-4 program is producing only about 40% good data.

- (3) The use of only three parameters almost surely reduces the accuracy of calculations when compared to the standard MCR. This is true even for relatively simple airplanes.

7.2.2.2.2 VGH Costs

The data of the Task I report estimates the VGH method at \$14 per flight hour. This is compared to approximately \$83 per flight hour for some MCR methods. The relative simplicity of the equipment and the non-time history data reduction methods are responsible for this decreased cost.

7.2.2.3 MSR System

7.2.2.3.1 Advantages and Disadvantages

Based on the assumption that the supporting resources (digital transcribing unit (DTU) machines, tapes, etc.) are available from the existence of an operational MSR IAT method, an MSR L/ESS program appears attractive, especially for some type airplanes. This is true for the case where only a few instruments are required to gain insight to the loading of the A/F/T airplane. For example, if an airplane has several critical points in the wing, fuselage, and tail section, it is highly likely that three of four strategically placed instruments will be able to give enough data to allow effective interpolation for numerous other points. Principal disadvantages of the MSR are the ones itemized in paragraph 6.2.2.2. These are drawbacks of the MSR method itself and not its application to L/ESS.

The MSR has been particularly effective in the case of the A-7D mini L/ESS program. The A-7D is an example of an airplane where most of the critical structural points are in or near the wing. The wing stresses are particularly sensitive to n_z . The MSR was used to update the relationship (i.e., provide stress spectra at critical wing locations) between n_z and strain. This program is discussed in Appendix C. More complicated airplane configurations (with rolling tails, canards, etc.) may not benefit as heavily from a simple MSR L/ESS program. For this reason, the MSR is not considered

to be a general L/ESS method.

7.2.2.3.2 MSR L/ESS Costs

The costs of an MSR L/ESS system are judged to be the least expensive of all. Assuming that three to four instruments are used on an airplane, it is believed that the cost will be approximately \$11 (three and one half times the single MSR costs) per flight hour. This prediction, along with the high accuracy inherent with recording strain directly, gives the MSR a theoretically high overall effectiveness score discussed in paragraph 7.2.3.

7.2.2.4 Microprocessor Based Systems

7.2.2.4.1 Advantages and Disadvantages

The advantages of the hypothesized MP/SC L/ESS method as outlined below are the high accuracy associated with recording strain directly and the automated data processing features that are possible. It is believed that an electronic, computer-based operation will fundamentally be more reliable and systematic than methods involving mechanical operations.

A disadvantage, as far as immediate, general application to IAT and L/ESS is concerned, is that a complete method is not available. Industry sources state that the method is entirely feasible, possible, and desirable, but is not available because no agency has financed its development.

Another disadvantage is that the method is based on the use of electrical strain gages. A discussion of this liability is given in paragraph 6.2.2.3.1. There is also no airplane response parameter historical data available.

The hypothesized MP/SC system discussed here is based on the capabilities of the IAT system described in paragraph 6.2.2.3. This basic capability is simply extended to accommodate the L/ESS duty by the provision of multi-channel operation.

Method Development - The method is described by the following steps:

Step 1. Determine the flight critical locations in the airplane

structure. The IAT reference point is assumed to be one of these. If it is, then duplicate data will be available for a check on this important location for the airplanes outfitted for L/ESS. This determination of the critical locations is made after the design loads analysis and a majority of the testing are complete. The design external load analysis coupled with a finite element internal loads analysis will provide functional relationships between spectrum variables and stresses at the chosen locations. These relationships can be verified during development flight testing. It is anticipated that the number of independent flight critical locations can be held to approximately 25 or less. These locations are to be appropriately instrumented and wired (on the production line) with strain gages. Each location will have a primary and a back-up gage.

Step 2. Analytically generate a series of rational stress spectra for each of the critical locations. These spectra will appear as Figure 7-1 and can be generated from the theoretical relationships between mission parameters and strain established in Step 1.

Step 3. Perform tests on specimens representing each of the critical locations for each of the rational spectra. This will provide a data bank of the form shown in Figure 7-1.

Step 4. Relate the ordinates crack length (a) of Figure 7-2 to damage indices and express these DI as a function of the number of occurrences of the discrete load levels that constitute the spectra.

The method for accomplishing the L/ESS function is to monitor and analyze the i locations for the selected airplanes for the three year duration of the program. The data taken from the L/ESS will be of the same form as Figure 7-1 and can be easily compared location by location with the assumed design strain exceedance data. If the operational usage is greatly different than the rational usages assumed for design, the damage rates may be determined from the damage relations developed in Step 4.

HYPOTHESIZED MP STRAIN DATA

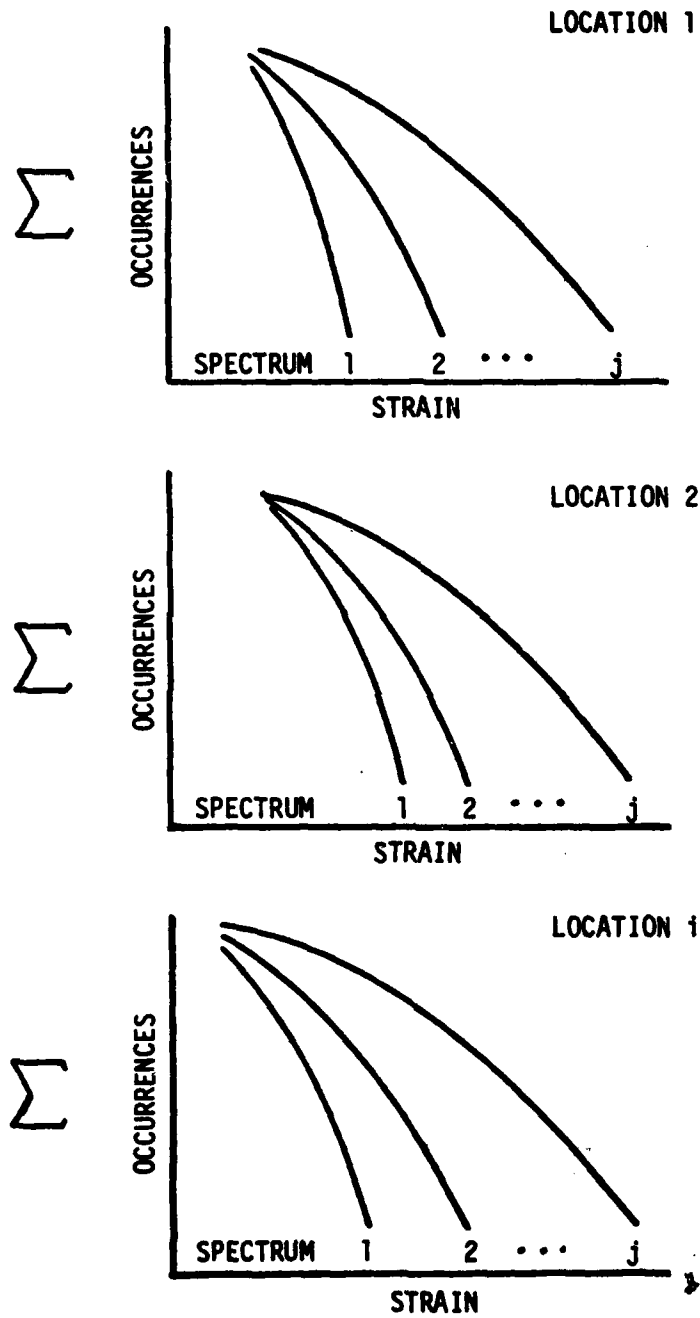


Figure 7-1

HYPOTHESIZED MP CRACK GROWTH DATA

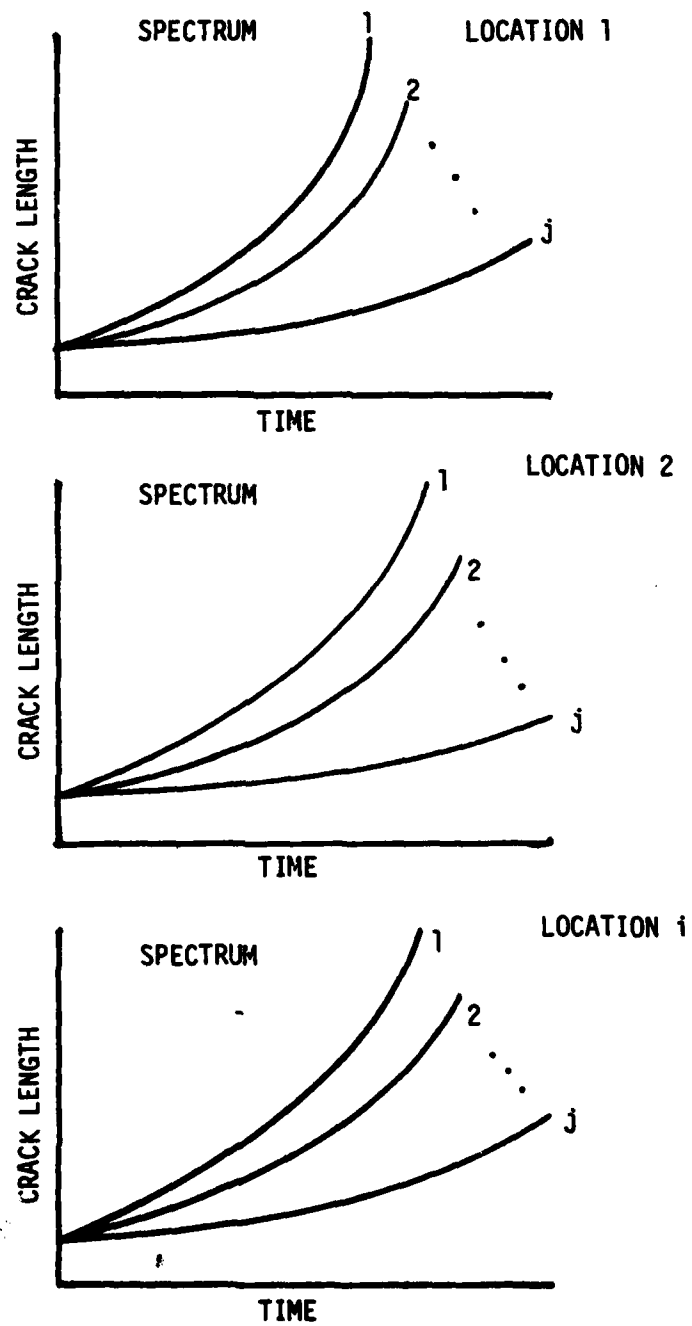


Figure 7-2

The possibility of being able to compare actual strain accumulation data from the operational force with the data assumed for the design appears to provide the essence of the L/ESS objective. The microprocessor can be expected to perform some of the calculations involved in this comparison of data. For example, the microprocessor may check the damage accumulation rate of each location, compare this rate with the previously calculated rates due to the original spectra, interpolate or extrapolate between appropriate spectra and describe current usage to the structural manager quantitatively.

If the IAT reference point is available, the L/ESS data will provide an update to the IAT damage or damage rate algorithm. A MP/SC IAT coupled with a MP/SC L/ESS system would be highly complementary to one another.

7.2.2.4.2 MP Costs

Cost data for a microprocessor based L/ESS system is difficult to define because of the lack of precise specifications. The largest unknown is that of development cost. Members of the industry stated that the development cost of a MP based IAT system will result in an overall cost that is competitive with the CA method. This estimate applies to a one channel device. The costs of multiple channels needed for L/ESS will increase as discussed in Section 6.

The relative cost estimate to be used here is that the MP based system will be competitive with the VGH recorder. The MP will probably demand more channels than the VGH but the costs are expected to be no more because of the automation features of the MP. The data reduction is estimated to be relatively simple for the case where time histories are not being used.

7.2.2.5 Alternate L/ESS Methods

This section is included to discuss possible methods of supplementing the L/ESS function with auxiliary data sources. These methods have not been analyzed completely and thoroughly for the L/ESS application, but each appears to have some interesting features.

Air Combat Maneuvering Instrumentation (ACMI)

The ACMI is a capability that has been developed by the Air Force to provide detailed information to training coordinators during the pilot training syllabus. The method consists of an electronic pod attached to a store station of each airplane flying the ACMI range. The pod contains instrumentation of each airplane response parameters. This data is telemetered to a ground station for processing and display. The display mechanism includes simulated images of the airplanes during the maneuvers.

The Air Force presently maintains ranges that will accommodate air-to-air engagements or encounters between two or more airplanes. Soon to be available are ranges that will duplicate this capability for air-to-ground activities. It is expected that a great majority of the structural damage is incurred (for most A/F/T aircraft) during these severe maneuvers. For these cases, it appears that the ACMI data could be subjected to processing and sorting to furnish data for regression equations that would calculate strain spectra. The ACMI technique would also reflect at least some changes in force pilot techniques, gross weight changes, fuel programming, etc., by recording these parameters for the airplanes using the range. The intriguing aspect of ACMI application is the cost. The multi-million dollar instrumentation and data acquisition system is already available. The additional cost of an application to structural needs appears to be relatively small.

Aircraft Simulators

A L/ESS program useful for an early look for some aircraft might be realized in an application of simulators. There are simulators available that closely approximate the characteristics of airplanes. Use of this simulated flying seems to have the possibility of an application to the L/ESS function in at least a supplemental or preliminary role.

Multivariable Table Expansions

It has been shown in at least some airplanes, that a key parameter such

as vertical acceleration can be related to other response parameters in a probabilistic fashion. Data in this form, called statistical multivariable table, contains essentially the same information as that acquired by an MCR program. The airplane response parameter would not be measured simultaneously, but would be generated by the methods of probability. This generation would be based on characteristic data (for the airplane in question) acquired from an MCR program and could at least supplement L/ESS data.

7.2.3 Comparison of Monitoring Techniques

As mentioned above, the methods discussed here are divided into two categories. A category containing the MCR and MP methods, which are suitable in theory for application to any airplane, and a category containing the MSR and VGH methods. These latter methods are not considered to be available for application to the general case. However, in order to summarize the methods' relative merits, it will be assumed that the appropriate method is being used in the most efficient application. Table 7.1 presents a summary of the relative merits of the methods. Based on the cost data of the Task I report and Section 6 of this report, it is concluded that an MSR method is least expensive. Approximately the same in overall cost are the MP and VGH methods. The MCR is the most expensive.

Most accuracy is given to the MP method since it records the strain (or stress) spectra directly. In the event that a non-recorded location turns up critical, it is estimated that interpolation or extrapolation of recorded spectra data would allow accurate predictions of the spectra at this location. The MSR is rated second in accuracy for the same reasons. The liability of this method is the assumption that fewer instruments would be used than for the MP.

Third most accurate is the MCR. Although good results are possible with the regression approach, there is no substitute for direct recording of the

strains to obtain the spectra. Rated last for accuracy is the VGH method. The reason for this is the fewer number of parameters available.

7.3 L/ESS SYSTEM IMPLEMENTATION

The successful implementation of an effective L/ESS system depends not only on a prudent method selection, but also on the education of the support personnel in the field. The present methods in use could be substantially improved if the quality of the support activity was commensurate with the design of the method. Therefore, first priority goes to development of adequate cooperation of the support activities in the field.

The selection of a low complexity system requiring simplified data handling should result in high data return at reasonable cost. It is projected that the recommended MP/SC system constitutes the proper combination of elements to result in accurate data in the required quantities. The following summarizes the principal steps in the execution of the MP based L/ESS system recommended here.

Step 1. Assume that the system described in paragraph 7.2.2.4.1 is in place on 10 to 20% of the operational airplanes of a given model. It is suggested that the strain exceedance data for each of the structural locations will be read from the MP visual readout approximately once a calendar quarter. (The problem flags will be monitored more frequently than quarterly.) The bookkeeping data will be similar to that described in the IAT discussion. For the L/ESS effort there will be considerably more information to be recorded than for IAT. If there are twenty channels of data, up to 200 blanks will require strain exceedance values. It is recommended that all airplanes at a given base be interrogated by a dedicated team to acquire the L/ESS data. Having a small team, say two persons whose principal duty is to take this data, is expected to greatly reduce mistakes. This may not be a full-time job for the team, however.

Step 2. The forms containing the data from three month's period will

be mailed to the structural manager organizations (such as the contractor and ASIMIS). The data will be processed into exceedances of strain at the structural locations. The exceedance curves may be compared to the distribution of rational design spectra discussed above. The data may be analyzed by addressing damage, damage rates, or correlation of spectra. In the event that one or more of the strain gages that are inaccessible malfunction, it is expected that relationships between the remaining ones would be available to allow the reconstruction of lost data.

Having the IAT and L/ESS methods closely connected in operational equipment and procedures cause the system to be complementary to each other and result in the best data for the investment of resources.

TABLE 7.1
L/ESS METHODS OVERALL RANKING

METHOD	COST RATING	ACCURACY RATING
MP/SC	2	1**
MSR	1*	2
VGH	2	4
MCR	4	3

***Indicates Least Expensive**

****Indicates Most Accurate**

8.0 CONCLUSIONS AND RECOMMENDATIONS

General conclusions resulting from this investigation into the Air Force FM activities are:

- (1) The specifications and controlling documents that define the FM/ASIP philosophy and requirements are generally adequate and well written.
- (2) Because of the requirements, it is unlikely that any aircraft that is procured under MIL-STD-1530A will have major structural anomalies.
- (3) The IAT function within the FM/ASIP group is working best and has the fewest problems.
- (4) The L/ESS activity is working least well and has the most problems. These problems are associated with inadequate support and diligence on the part of the field (user) activities.
- (5) The FM effort of the five-task Air Force aircraft structural integrity program is the most important. This is because the IAT and L/ESS data bank provides the informational resources to deal with structural problems.

Detailed conclusions regarding the FM methods addressed herein are:

- (1) Strain exceedance data is the optimum resource for IAT task. The application of the MSR represented a significant step in this direction but a potential improvement is the use of electronic means in lieu of mechanical means to acquire the data. The electronic devices can quality check and otherwise process data that the mechanical devices cannot.
- (2) Use of strain exceedance data lends itself to simplified algorithms for damage calculations. These simplified expressions are desirable for application to a low capacity microprocessor IAT method.
- (3) The crack growth gage cannot achieve the status of a general IAT method without additional substantial research effort. It is further recommended that these research resources be dedicated to the development of microprocessor methods instead of CGG methods if only one can be developed.

(4) The L/ESS objectives can be met with an accumulation of actual strain exceedance spectra versus the time history method. The direct strain spectra method would provide no airplane response parameter history, but there is doubt that this data has an application that justifies its costs. If shown to be necessary, the cost of the airplane response data will decline if acquired via a microprocessor method.

The following recommendations are made in the interest of improving and enhancing the efficiency of the FM/ASIP activities.

(1) The establishment of an office (as described in Section 3.0) within the Air Force that would have responsibility for approving the details of all FM/ASIP data acquisition, processing, and reduction systems. This responsibility would be operative for all airplanes the Air Force procures and would provide for the continuity and accumulation of experience with FM/ASIP data problems.

(2) Renewed emphasis be placed on the data collection activities by the user commands. This is tantamount to increasing the priority of the data acquisition and equipment maintenance functions.

(3) It is recommended that expensive structural inspection be followed by an appropriate rework of the locations involved whether a flaw is found or not. The rationale for this is that if the resources are invested in exposing a location to inspection, a rework will combat any damage induced by the teardown and will treat an undetected flaw.

(4) It is recommended that the IAT and L/ESS functions be combined or at least be more closely coordinated. This may be accomplished by the use of state-of-the-art electronic methods such as microprocessors.

APPENDIX A

A-7D/F-4 COUNTING ACCELEROMETER DI EQUATIONS/ERROR ANALYSES

A-7D STUDY

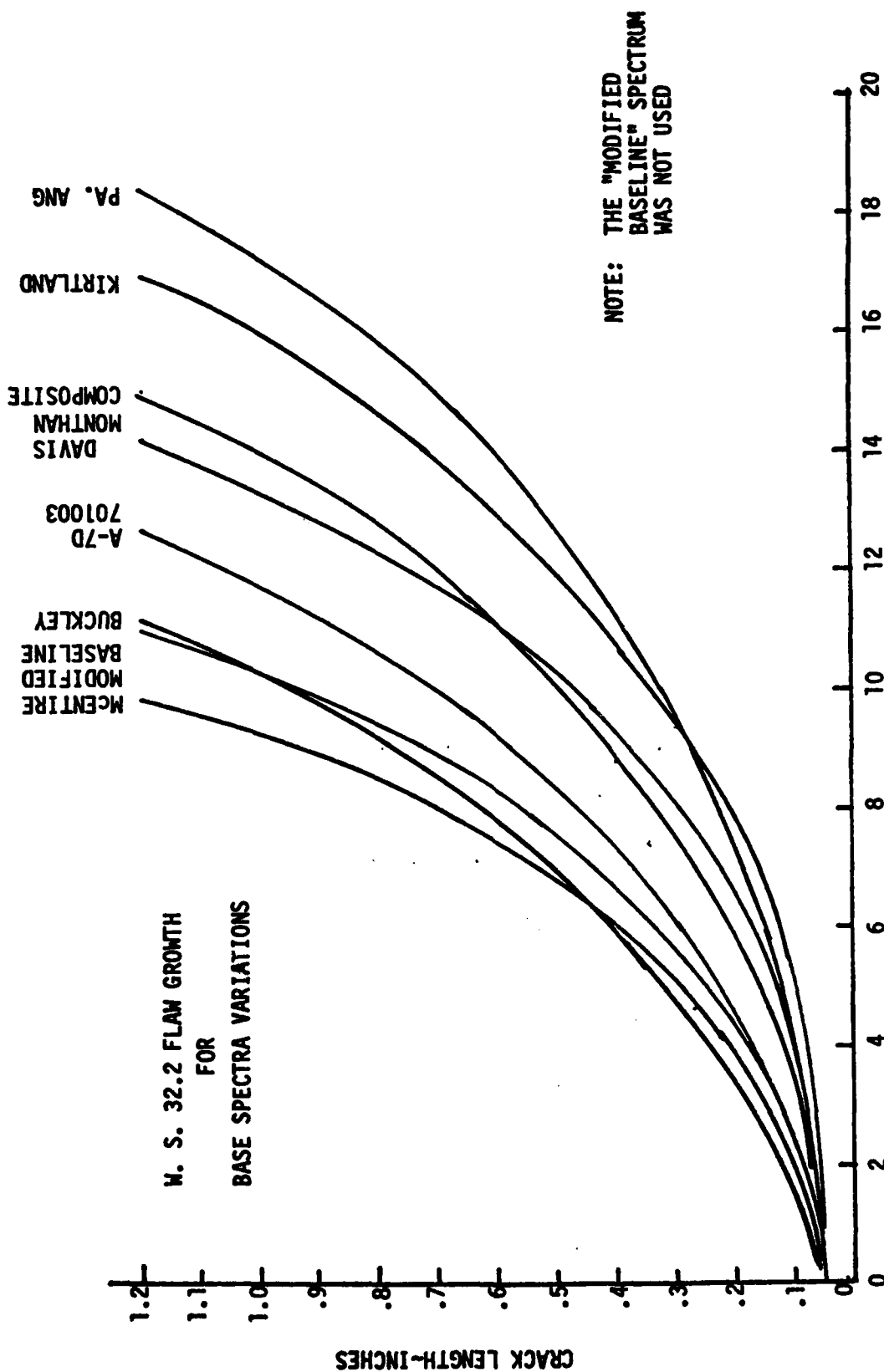
The A-7D DI equation discussed in Section 6 of the report body expresses the instantaneous damage index as a function of flight time and CA counts. This equation, developed as an experimental method and intended to simplify the damage algorithm for possible application of MP methods, is derived from laboratory coupon test data. The equation defines damage index which is ratioed from crack length. Described below is a description of the derivation and a comparison of the equation results with data from the Air Force A-7D damage model.

The equation, of the form

$$DI = A_0 + A_5 E_5 + A_6 E_6 + A_t T,$$

was derived from the coupon test data repeated as Figure A-1. This data was analyzed by a stepwise multiple regression in the following manner: Each curve was read from spectrum time at the following crack length, $a = 1.2, .8, .4, .2, .1, .075$, and $.05$ inches, where a crack length of 1.2 inches corresponds to the maximum DI of 3.05. This arbitrary value for the maximum DI for the A-7D airplane results from the ASIP Analysis which showed the airplane with a life of 12,200 baseline hours. The original design life was 4000 hours. Dividing 12,200 by 4,000 yields the 3.05 value. Reference 9 provides additional details.

The DI and constituent CA occurrences are then factored by the ratio of spectrum time at a crack length divided by the time corresponding to the 1.2 in crack length. For example, the input into the regression analysis for the McEntire spectrum is:



THOUSAND FLIGHT HOURS

FIGURE A-1

<u>Crack Length</u>	DI	E ₅	E ₆	E ₇	E ₈	<u>Time</u>
1.2 in.	3.05	18903	4223	387	11	9884
.8	2.62	16256	3632	333	9	8500
.4	1.82	11284	2521	231	7	5900
.2	1.16	7172	1602	147	4	3750
.1	.59	3634	812	74	2	1900
.075	.37	2305	515	47	1	1250
.05	.15	956	214	20	1	500

The seven spectra, each read at seven crack lengths, provided a total of 49 observations for the regression analysis. (It is assumed that for an actual application, more than seven spectra would be used in order to provide a wider range of airplane usages.)

The resulting equation was used in an error analysis to evaluate its quality. Part of the error analysis is discussed in Section 6.0. The remaining error analysis effort was to compare the simple DI equation with the results of an Air Force ASIMIS damage run. This comparison was made for all A-7D airplanes having more than about 50 flight hours. The results, airplane by airplane, is given in Table A.1. The composite error for all airplanes between the official DI values and ones from the experimental equation is 5.02%. It might be added that the majority of the differences were such that conservative value was given by the experimental equation.

F-4E STUDY

A similar study was conducted on a sample 53 F-4E airplanes. Used for comparison was data calculated by the F-4 contractor's damage model.

The simplified DI equation

$$DI = A_0 + A_3E_3 + A_4E_4 + A_5E_5 + A_6E_6$$

for this airplane did not have airplane flight (spectrum) time as an independent variable. The data of Figure A-2 demonstrates little apparent

TABLE A.1
COMPARISON OF A-7D DAMAGE INDICES CALCULATED
BY ASIP EQUATION AND FM EQUATION

(For airplanes having more than 50 flight hours; Ref. data through September, 1978)

TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %
674585	.107	.108	0.9	696210	.329	.348	5.8	700930	.324	.351	8.3
6	.153	.149	2.7	12	.379	.404	6.6	1	.308	.342	11.0
688220	.141	.140	0.7	3	.301	.319	6.0	2	.267	.282	5.6
2	.246	.248	0.8	4	.358	.374	4.5	3	.319	.337	5.6
3	.337	.338	0.3	5	.298	.312	4.7	4	.299	.317	6.0
4	.193	.195	1.0	6	.315	.329	4.4	5	.332	.357	7.5
5	.231	.243	5.2	7	.336	.353	5.1	6	.337	.354	6.6
6	.300	.302	0.7	8	.310	.329	6.1	7	.359	.381	6.1
7	.302	.301	0.3	9	.267	.278	4.1	8	.164	.167	1.8
8	.340	.345	1.5	21	.294	.320	8.8	9	.346	.364	5.2
9	.236	.251	6.4	2	.261	.280	7.3	40	.301	.316	5.0
30	.332	.348	4.8	3	.245	.262	6.9	1	.279	.286	2.5
1	.316	.329	4.1	4	.203	.212	4.4	2	.332	.357	7.5
696188	.334	.347	3.9	5	.344	.357	3.8	3	.298	.302	1.3
9	.187	.197	5.3	6	.320	.338	5.6	4	.286	.296	3.5
90	.253	.267	5.5	7	.294	.307	4.4	5	.168	.177	5.4
1	.273	.266	2.6	8	.322	.334	3.7	6	.273	.284	4.0
2	.075	.079	5.3	9	.264	.280	6.1	7	.235	.246	4.7
3	.275	.288	4.7	30	.333	.350	5.1	8	.319	.331	3.8
4	.294	.307	4.4	1	.258	.271	5.0	9	.140	.152	8.6
5	.273	.286	4.8	2	.295	.308	4.4	51	.265	.276	4.2
6	.178	.190	6.7	3	.337	.351	4.2	2	.320	.331	3.4
7	.302	.315	4.3	4	.142	.154	8.5	3	.295	.306	3.7
8	.263	.277	5.3	5	.277	.297	7.2	5	.262	.277	5.7
9	.311	.320	2.9	6	.349	.373	6.9	6	.306	.313	2.3
200	.262	.268	2.3	7	.236	.250	5.9	7	.279	.293	5.0
1	.328	.342	4.3	8	.252	.264	4.8	8	.295	.300	1.7
2	.316	.333	5.4	9	.284	.297	4.6	9	.264	.281	6.4
3	.348	.364	4.6	40	.345	.352	2.0	60	.311	.326	4.8

TABLE A.1 (cont'd)

TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %
696205	.334	.341	2.1	696241	.328	.350	6.7	700961	.275	.285	3.6
6	.342	.360	5.3	2	.295	.312	5.8	2	.270	.283	4.8
7	.329	.345	4.9	3	.311	.330	6.1	3	.317	.342	7.9
8	.251	.263	4.8	4	.342	.358	4.7	4	.353	.361	2.3
9	.303	.331	9.2	700929	.240	.250	4.2	5	.337	.364	8.0
700966	.370	.387	4.6	701000	.266	.276	3.8	701035	.224	.238	6.2
7	.332	.350	5.4	1	.243	.254	4.5	6	.283	.295	4.2
8	.294	.313	6.5	2	.317	.324	2.2	7	.274	.297	8.4
9	.261	.287	10.0	3	.278	.298	7.2	8	.204	.213	4.4
70	.301	.305	1.3	4	.257	.264	2.7	9	.237	.242	2.1
1	.350	.368	5.1	5	.251	.262	4.4	40	.243	.247	1.6
2	.303	.326	7.6	6	.280	.289	3.2	1	.215	.219	1.9
3	.240	.255	6.2	7	.316	.327	3.5	2	.242	.253	4.5
4	.356	.365	2.5	8	.243	.254	4.5	3	.226	.250	10.6
5	.263	.276	4.9	9	.267	.281	5.2	4	.231	.242	4.8
6	.341	.353	3.5	10	.262	.273	4.2	5	.254	.267	5.1
7	.308	.328	6.5	1	.269	.289	7.4	6	.223	.231	3.6
8	.301	.307	2.0	2	.219	.230	5.0	7	.254	.278	9.4
9	.275	.294	6.9	3	.258	.268	3.9	8	.182	.189	3.8
80	.276	.284	2.9	4	.285	.299	4.9	9	.159	.168	5.7
1	.309	.327	5.8	5	.242	.254	5.0	50	.205	.214	4.4
2	.330	.344	4.2	6	.204	.206	1.0	1	.212	.223	5.2
3	.312	.329	5.4	7	.215	.220	2.3	2	.228	.245	7.5
4	.276	.276	0	8	.204	.213	4.4	3	.215	.228	6.0
5	.268	.282	5.2	9	.251	.262	4.4	4	.297	.303	2.0
6	.291	.300	3.1	20	.245	.263	7.3	5	.243	.245	0.8
7	.231	.232	0.4	1	.248	.259	4.4	6	.231	.248	7.4
8	.321	.346	7.8	2	.287	.305	6.3	710292	.284	.263	8.0
9	.322	.326	1.2	3	.233	.243	4.3	3	.272	.264	3.0

TABLE A.1 (cont'd)

TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %
700990	.272	.289	6.2	701024	.097	.108	11.3	710294	.232	.250	7.8
1	.282	.297	5.3	5	.275	.291	5.8	5	.210	.211	0.5
2	.272	.281	3.3	6	.252	.271	7.5	6	.276	.288	4.3
3	.282	.289	2.5	7	.269	.277	3.0	7	.252	.243	3.7
4	.281	.294	4.6	8	.244	.254	4.1	8	.254	.258	1.6
5	.305	.316	3.6	9	.236	.247	4.7	9	.283	.294	3.9
6	.308	.311	1.0	30	.276	.289	4.7	300	.222	.235	5.9
7	.106	.114	7.5	1	.264	.287	8.7	1	.204	.205	0.5
8	.254	.267	5.1	2	.248	.263	6.0	2	.218	.219	0.5
9	.290	.304	4.8	3	.235	.241	2.6	3	.151	.149	1.3
				4	.213	.220	3.3	4	.264	.278	5.3
710305	.090	.102	13.3	710341	.182	.190	4.4	710376	.152	.159	4.6
6	.148	.152	2.7	2	.157	.162	3.2	7	.123	.125	1.6
7	.330	.341	3.3	3	.158	.157	0.6	8	.022	.022	0
8	.245	.259	5.7	4	.201	.205	2.0	9	.189	.199	5.3
9	.230	.242	5.2	5	.228	.239	4.8	720170	.204	.216	5.9
10	.047	.053	12.8	6	.093	.100	7.5	1	.255	.273	7.1
1	.322	.339	5.3	7	.128	.129	0.8	2	.117	.115	1.7
2	.036	.044	22.2	8	.154	.160	3.9	3	.191	.204	6.8
3	.263	.287	9.1	9	.212	.225	6.1	4	.190	.201	5.8
4	.269	.286	6.3	50	.171	.180	5.3	5	.200	.215	7.5
5	.298	.311	4.4	1	.176	.183	4.0	6	.157	.168	7.0
6	.049	.056	14.3	2	.213	.223	4.7	7	.173	.182	5.2
7	.292	.300	2.7	3	.222	.228	2.7	8	.228	.246	7.9
8	.287	.317	10.5	4	.284	.287	1.1	9	.186	.194	4.3
20	.242	.264	9.1	5	.207	.215	3.9	80	.184	.191	3.8
1	.251	.268	6.8	6	.183	.179	2.2	1	.222	.222	0
3	.280	.292	4.3	7	.051	.055	7.8	2	.175	.184	5.1

TABLE A.1 (cont'd)

TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %
710324	.186	.190	5.6	710358	.210	.211	0.5	720183	.182	.190	8.6
5	.206	.221	7.3	9	.332	.303	9.6	4	.197	.209	14.8
6	.284	.302	6.3	60	.199	.212	6.5	5	.187	.195	4.3
7	.264	.277	4.9	1	.377	.299	26.1	6	.150	.155	3.3
8	.059	.056	5.4	2	.175	.181	3.4	7	.175	.181	3.4
9	.219	.229	4.6	3	.224	.238	6.2	8	.187	.194	3.7
30	.157	.160	1.9	4	.192	.201	4.7	9	.125	.130	4.0
1	.280	.296	5.7	5	.271	.273	0.7	90	.107	.110	2.8
2	.240	.244	1.7	6	.182	.194	6.6	1	.167	.173	3.6
3	.167	.175	4.8	7	.163	.163	0	2	.183	.194	6.0
4	.476	.346	37.6	8	.187	.204	9.1	3	.164	.179	9.1
5	.255	.272	6.7	9	.198	.203	2.5	4	.193	.205	6.2
6	.052	.055	5.8	70	.170	.173	1.8	5	.150	.162	8.0
7	.138	.134	3.0	1	.192	.194	1.0	6	.211	.211	0.5
8	.197	.206	4.6	2	.022	.025	13.6	7	.288	.261	10.3
9	.205	.215	4.9	3	.112	.117	4.5	8	.187	.191	2.1
40	.143	.148	3.5	4	.235	.219	7.3	9	.194	.206	6.2
				5	.109	.113	3.7	200	.152	.155	2.0
720201	.145	.148	2.1	720236	.140	.149	6.4	730997	.125	.134	7.2
2	.146	.150	2.7	7	.142	.139	2.2	9	.104	.104	0
3	.196	.210	7.1	8	.221	.221	0	731000	.103	.099	4.0
4	.085	.087	2.4	9	.246	.255	3.7	1	.133	.143	7.4
5	.179	.194	8.4	40	.199	.207	4.0	2	.113	.114	0.9
6	.142	.144	1.4	1	.187	.193	3.2	3	.123	.126	2.4
7	.194	.203	4.6	2	.187	.196	4.8	4	.119	.123	3.4
8	.189	.195	3.2	3	.213	.215	0.9	5	.135	.130	3.8
9	.168	.173	3.0	4	.170	.177	4.1	6	.136	.139	2.2
10	.124	.128	3.2	5	.141	.145	2.8	7	.106	.112	5.7
1	.178	.181	1.7	6	.179	.197	10.1	8	.112	.113	0.9

TABLE A.1 (concluded)

TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %	TAIL NO.	ASIP D.I.	FM D.I.	DIFF. %
72021 2	.183	.195	6.6	72024 7	.133	.145	9.0	73100 9	.125	.135	8.0
3	.162	.162	1.9	8	.169	.178	5.3	10	.162	.163	0.6
4	.169	.180	6.5	9	.159	.154	3.2	11	.109	.114	4.6
5	.121	.127	5.0	50	.179	.188	5.0	12	.134	.141	5.2
6	.183	.190	3.8	1	.158	.164	3.8	13	.107	.114	6.5
7	.225	.233	3.6	2	.201	.216	5.0	14	.079	.085	7.6
8	.213	.216	1.4	3	.133	.142	6.8	15	.134	.122	9.8
9	.153	.163	6.5	4	.157	.183	16.6	74173 7	.123	.129	4.9
20	.248	.254	2.4	5	.157	.167	6.4	8	.155	.135	14.8
1	.241	.222	8.6	6	.155	.162	3.2	40	.092	.098	6.5
2	.158	.161	1.9	7	.179	.183	2.2	1	.154	.132	16.7
3	.161	.169	5.0	8	.219	.225	2.7	2	.053	.053	0
4	.213	.218	2.3	9	.187	.201	7.5	3	.052	.060	15.4
5	.150	.152	1.3	60	.150	.155	3.3	4	.083	.091	9.6
6	.147	.157	6.8	1	.156	.154	1.3	6	.090	.091	1.1
7	.245	.243	0.8	2	.143	.140	2.1	7	.059	.065	10.2
8	.167	.179	7.2	3	.150	.156	4.0	50	.087	.084	3.6
9	.221	.222	0.5	4	.212	.206	2.9	1	.088	.091	3.4
30	.222	.233	5.0	5	.086	.085	1.2	2	.059	.064	8.5
1	.240	.278	15.8	73099 2	.200	.189	5.8	4	.062	.066	6.5
2	.137	.142	3.6	3	.098	.105	7.1	7	.060	.066	10.0
3	.213	.221	3.8	4	.154	.162	5.2				
4	.191	.201	5.2	5	.196	.180	8.9				
5	.166	.170	2.4	6	.166	.183	10.2				

correlation between flight time and DI. This lack of correlation was verified by the regression analysis. The comparison of the F-4E Contractor's DI with the experimental equation for the 53 airplanes is presented in Figure A-3. Here the "actual" DI is taken to be the contractor's calculation while the "predicted" is due to the experimental equation. The 45 degree line represents perfect correlation.

Another approach for making comparison between the to DI calculations was to investigate the environmental damage growth. To do this, one of the airplanes (#4232) was chosen at random, and the DI was progressively calculated for comparison to the Contractor's interim calculations. Table A.2 presents this data. Figure A-4 provides a graphic representation of the quality of the comparison for the interim data.

The F-4 airplane has a relatively complicated damage prediction procedure as reported in the Task I report. Under this procedure, the damage is calculated incrementally. This requires that the previous accumulated damage total be saved. The simple algorithm suggested here has two advantages: (1) it simplifies a relatively complex procedure, and (2) it calculates a total damage index and not an increment to be added to a previous sum.

The composite error for the comparison of the 53 airplanes is slightly less than 5%. This is considered very good and further, is in line with the A-7D analysis.

F4E DAMAGE INDEX VS. FLIGHT HOURS (53 AIRCRAFT)

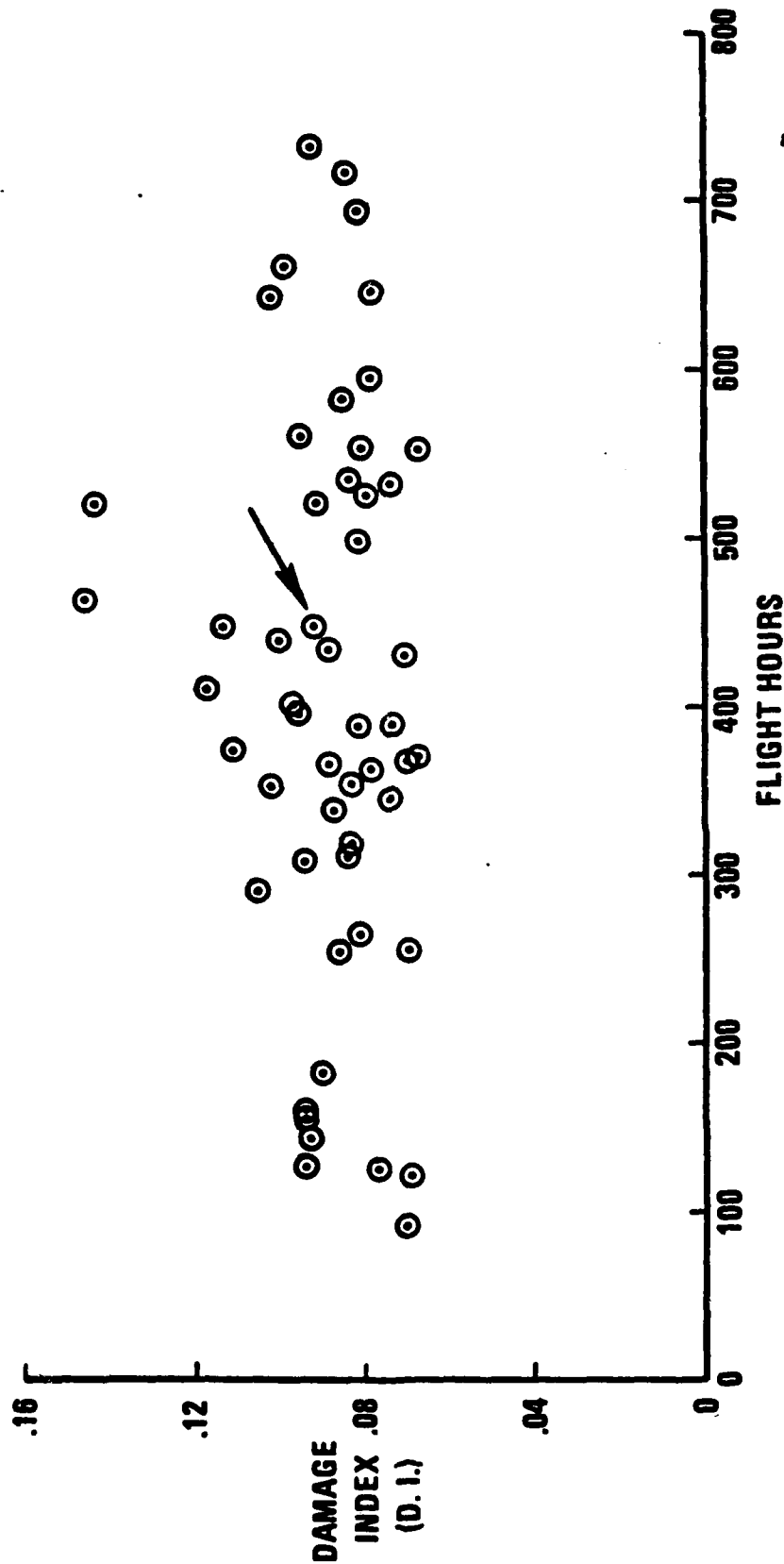


FIGURE A-2

CURVE-FIT OF F4E DAMAGE INDICES (53 AIRCRAFT)

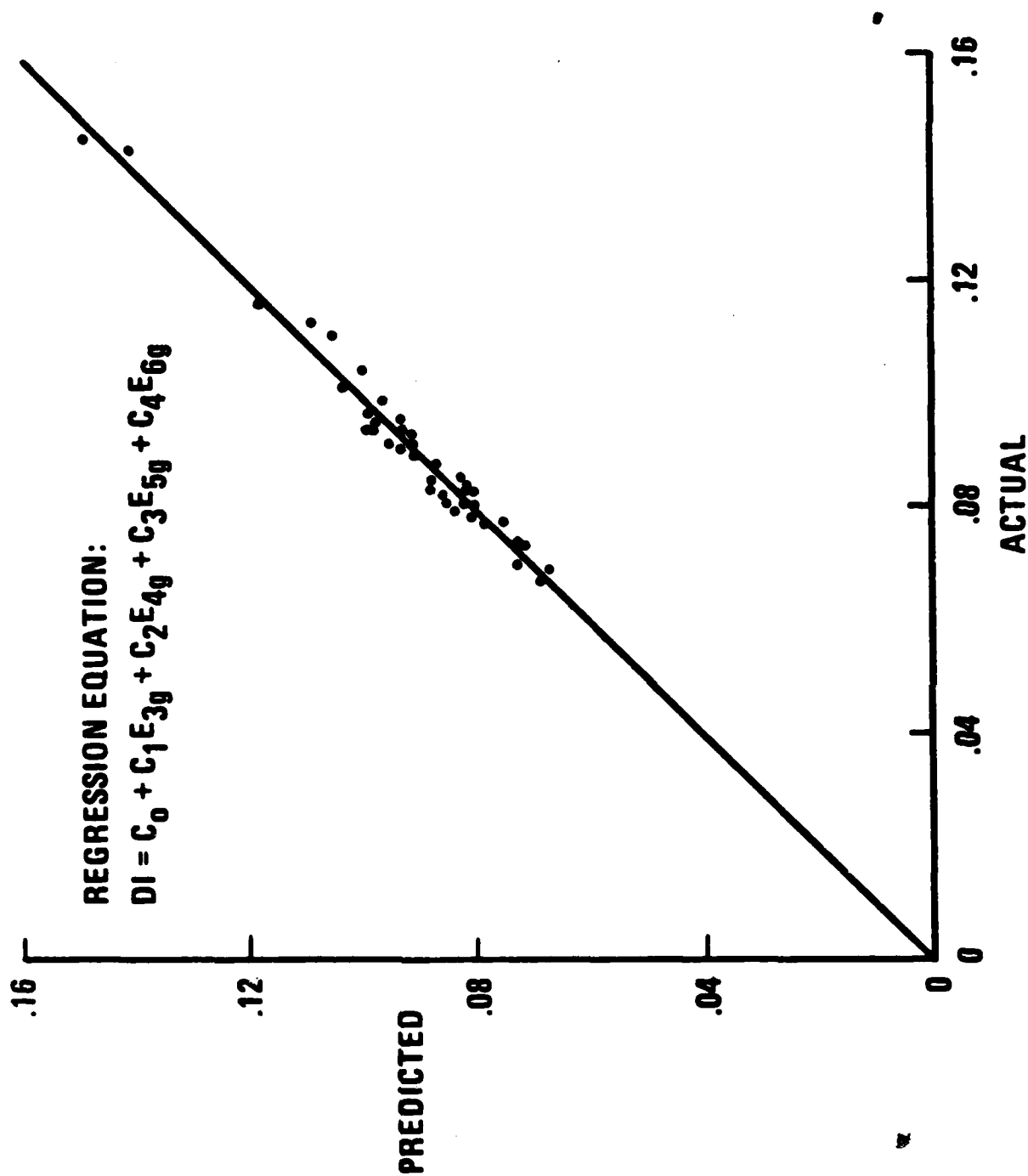


FIGURE A-3

TABLE A.2

F-4E INDIVIDUAL AIRCRAFT PRINTOUT

MAC NO. 4232		TOTAL EXCEEDANCES				TOTAL DAMAGE	
TOTAL FLT HRS.	USAGE	3g	4g	5g	6g	"ACTUAL"	PREDICTED
3	-	0	0	0	0	.0000	-.0020
12	MILD	47	15	7	2	.0010	-.0009
46	MILD	261	79	21	4	.0028	.0015
70	BASELINE	505	185	58	7	.0072	.0058
84	SEVERE	723	293	101	14	.0128	.0113
116	BASELINE	1063	415	140	24	.0196	.0178
147	MILD	1212	482	163	30	.0227	.0215
156	BASELINE	1291	520	179	30	.0241	.0229
165	MILD	1353	546	183	34	.0256	.0245
191	MILD	1416	578	197	36	.0270	.0262
214	BASELINE	1604	662	225	40	.0308	.0299
230	MILD	1690	699	240	41	.0320	.0315
254	BASELINE	1926	795	280	58	.0401	.0393
279	BASELINE	2165	897	328	74	.0485	.0472
299	SEVERE	2379	1012	384	96	.0581	.0571
332	MILD	2544	1074	404	107	.0625	.0619
357	SEVERE	2845	1203	463	117	.0700	.0694
388	BASELINE	3170	1354	530	134	.0803	.0792
426	MILD	3387	1441	563	139	.0838	.0835
448	SEVERE	3752	1613	621	147	.0915	.0911

F-4E DAMAGE INDEX COMPARISONS FOR MAC NO. 4232

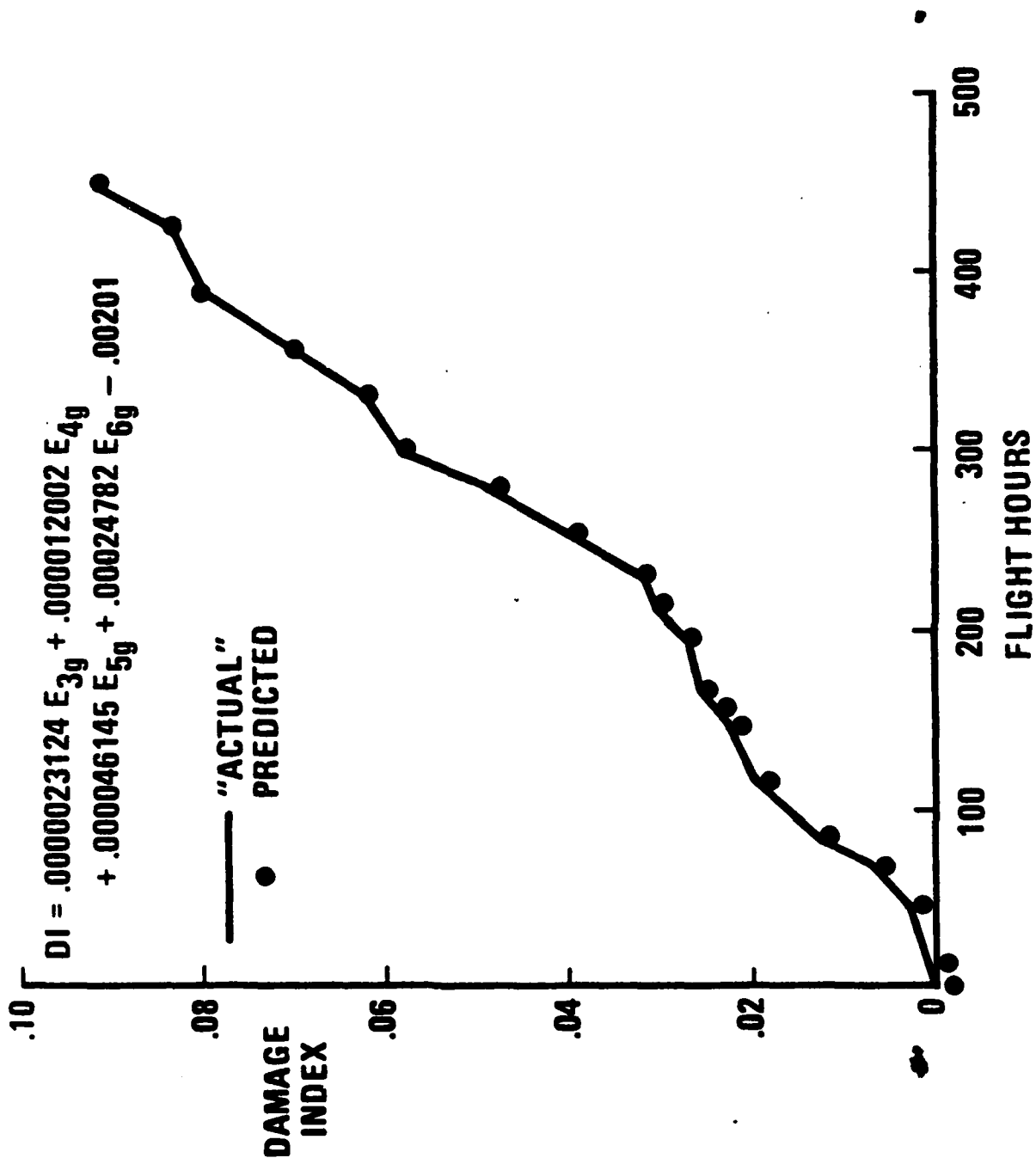


FIGURE A-4

APPENDIX B
EVALUATION OF DAMAGE TRANSFER AND
RELATIVE ERRORS OF CA AND MSR IAT METHODS

INTRODUCTION

In an attempt to maximize the structural useful life of its airplane weapon systems, the United States Air Force has introduced a concept called Force Management. The objective of this concept is to provide the methods and procedures for defining all force maintenance actions. These actions include structural inspections, structural rework if required, component replacement as required, and retirement. The mission of Force Management is to program these actions to optimize economic and safety considerations. The specifics of Force Management are delineated in MIL-STD-1530A [1].¹

This standard provides for a fracture mechanics approach to the airframe durability/fatigue life evaluation problem. That is, it is assumed that the structure has initial production flaws or cracks that require monitoring or tracking throughout the airframe's usage to preclude crack growth to critical proportions. Attendant requirements are also defined in MIL-STD-1530A and supporting specifications concerning the design of new airframes for inspectability, fail safety, and materials selection (for slow crack growth).

The basic elements of Force Management include an individual aircraft tracking program (IAT), a loads and environment spectra survey (L/ESS), and a force structural maintenance plan. The investigation described in this paper applies to, and was done in support of, the IAT functions of Force Management.

A primary objective of an IAT program under MIL-STD-1530A is to predict the potential growth of flaws in critical areas of each airframe. The flaw growth data are then used to derive maintenance intervals for individual aircraft. Before fracture mechanics techniques were available, this task was

¹Numbers in brackets refer to references listed at end of report.

accomplished by methods based on accumulated fatigue damage. This has resulted in two categories of IAT programs, one based upon fatigue damage and one upon crack growth damage calculations, depending upon when the aircraft was designed. Only one fighter/attack aircraft (the F-16) has been developed under the MIL-STD-1530A requirements although several have been evaluated using the methods of fracture mechanics.

The individual aircraft usage data for United States Air Force aircraft is acquired by use of an "activity indicator". There are presently two recording devices in use: the counting accelerometer (CA) and the mechanical strain recorder (MSR).

A counting accelerometer is a device consisting of a transducer that senses aircraft center of gravity vertical acceleration and a digital indicator that displays the cumulative occurrences of specific acceleration levels. An MSR is a self-contained mechanical device which senses and records total deformation over the effective gage length of the structure to which it is attached. A tensile deformation of the structure causes a stylus to scratch a metal foil tape contained in a cartridge. The excursion of the stylus is proportional to the deformation. The tape advances as successive recordings are made.

The basic objective of Individual Airplane Tracking is to use the data acquired from the airplane activity indicator in a fashion which allows periodic calculation of a damage index. This capability is the heart of the force management concept and is receiving considerable attention in an attempt to produce reliable and accurate results. The problem is basically one of having a very small amount of information in a case where a large amount is needed. Generally, an airplane will have only one indicator and a large number of structural locations that require tracking. The implementation of IAT then requires a transfer function that relates indicator data to damage at a reference location and methods of predicting damage at remote locations.

A fundamental difference between the CA and the MSR is that the CA requires one additional transfer function relating acceleration to stress at the reference location. That is, the stress that is calculated from a given load factor for the purpose of damage prediction assumes some average value for important flight parameters such as weight. An MSR records the stress (obtained from strain) directly without knowledge of the maneuver or flight condition that causes the loads.

The study reported here was directed at two questions inherent to the IAT process using CA and MSR: (1) How much error is introduced by use of the CA relative to the MSR in damage index calculations or life expended? (2) Can the damage rate at remote locations be correlated with the calculated damage rate at the reference location?

ANALYSIS

The approach to investigating the questions at hand consisted of choosing several structural locations in an airplane and analyzing the response of each location to usage spectra variations. This analysis was guided by the MIL-STD-1530A assumptions in initial flaws in safe crack growth structure. Failure was assumed when the applied stress intensity factor reached the critical stress intensity factor for the part thickness.

The airplane selected for this study is the USAF A-7D. The structural locations chosen are the eight described by Figures B-1 and B-2. The baseline usage spectrum chosen was derived during the A-7D USAF Aircraft Structural Integrity Program. Stresses were calculated by a finite element analysis of the structure as described in [8]. The structural locations were selected not because of their criticality, but to give a reasonable distribution of points in the airplane. In fact, to produce failure at the points selected, the theoretical stresses were increased to produce the final spectra.

Table B.1 itemizes the nine spectra variations used in the study.

These variations represent reasonable variations in airplane mission parameters. For example, reprogramming of fuel usage can cause weight variations of the magnitude shown. Table B.2 expresses the stress in terms of these variables.

The vertical and horizontal tail locations are made of 4340 steel while the remaining six locations are 7075-T6 aluminum. The initial flaw lengths are seen to be .01 inch for the steel and .05 inch for the aluminum. The EFFGRO fracture model [9] with the Vroman retardation option was used for the crack growth analysis.

A unique stress spectrum for each of the eight structural locations was generated for each of the 10 mission variations. A total of 80 EFFGRO crack growth analyses were then accomplished. Figures B-3 through B-9 are included to characterize the results of these crack growth histories. The end point of each curve denotes fracture. It is seen that the content of the different spectra impact the crack growth rates as well as the critical crack lengths.

Dividing the (spectrum) time to failure for each of the spectra by the time to failure under the baseline spectrum results in the normalized crack growth life data of Table B.3. The variations in life range from a -88% in the case of the horizontal tail under spectrum 4 to +800% for the same location under spectrum 3. Variations of this magnitude are difficult to explain physically and likely point out that the analysis is method limited in the case of the horizontal tail. That is, the method of predicting the horizontal tail stresses possibly fails for variations of this magnitude in the spectrum parameters. It is judged that trends in the results are preserved, however.

The significance of the data of Table B.3 is that large changes in life are apparent under the influence of relatively small changes in Mach number and weight. The counting accelerometer is blind to both these

variables. The counting accelerometer is at least partially blind to the mission variations represented by spectra 8, 9, and 10. The Mach number and weight experience effective variations by shifting the time spent in the subject missions. The MSR has an obvious advantage in these cases since it reflects the actual load experienced at the location.

Figures B-10 through B-13 address the remaining question with respect to IAT - that of being able to track the damage state at locations remote to the reference location. In these figures, the crack growth curve data is normalized to give an indication of the rate of damage at the stations remote to WS 32, the reference for the A-7D. The data is normalized as follows: for a given location, the minimum failure crack length was read for each spectrum. Each of the spectrum times corresponding to these lengths was divided by the time it took to reach the minimum length for the baseline spectrum. The normalized values of each of the locations are plotted against the values of the reference station, wing station 32. Note that the 45° line on the graphs represents perfect correlation of the damage at the various locations with the damage at the reference. Note also that the lower half of the divided quadrant represents conservative comparisons while the upper half is non-conservative.

An examination of the data in Figures B-10 through B-13 reveals that the error in the damage rates of wing station 53, pylon stub hole, and the outer wing panel, relative to the reference is especially good. The average of the variations in damage rate for these locations is 5%. For the wing attach lug, the variation from perfect correlation is about 10% and for the longeron, about 18%. These variations are considered moderate when taken as an average, but the maximum variations for particular spectra are 27% and 48%, respectively. These large variations make the usefulness of such damage transfer somewhat tenuous for these stations. The variations in the damage

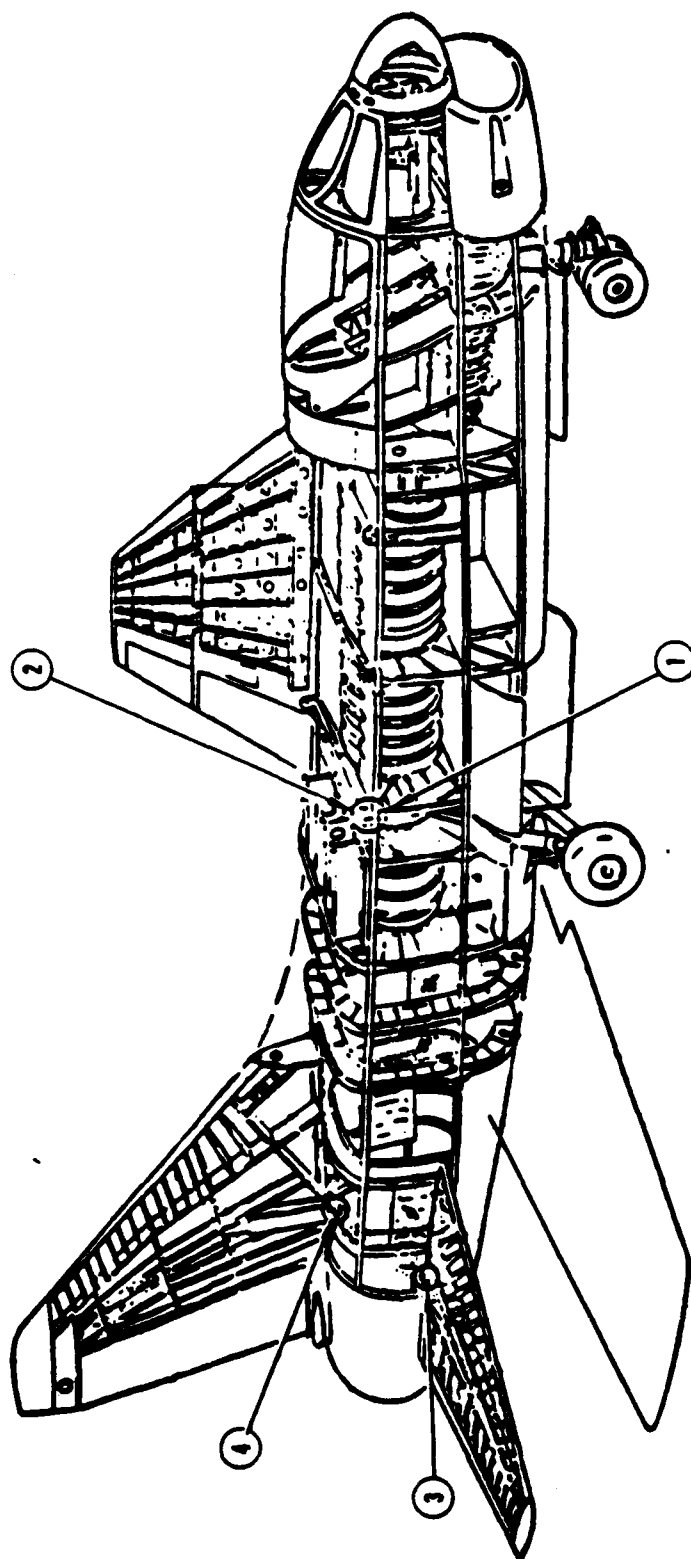
rate correlations for the two tail stations are considered completely out of order.

CONCLUSIONS

The conclusion concerning the relative superiority of the CA versus the MSR for IAT is that the MSR is considerably more efficient and accurate in terms of providing a damage index per se. A thorough cost analysis and comparison of the two methods could mitigate this ranking to some extent. For example, it could be that the supposed higher cost of the data retrieval and processing for the MSR could outweigh the accuracy liabilities of the CA. Also the CA accuracy can always be improved by frequently updating the stress to acceleration relationship. This process is a cost item, however. For purposes of this investigation, the MSR is chosen as the superior method.

A conclusion with respect to the second IAT question is much more differential. It is seen that some remote locations can be damage tracked through a reference station while others cannot. Gross indications here are that locations associated with the wing track well, the fuselage not so well, and the tails not at all. For airplanes having critical structure only in the wing, it follows that successful IAT is highly likely with a single activity indicator. For airplanes with a wide distribution of critical locations, multiple indicators may be required. In any event, careful analysis is required.

FUSELAGE-EMPENNAGE

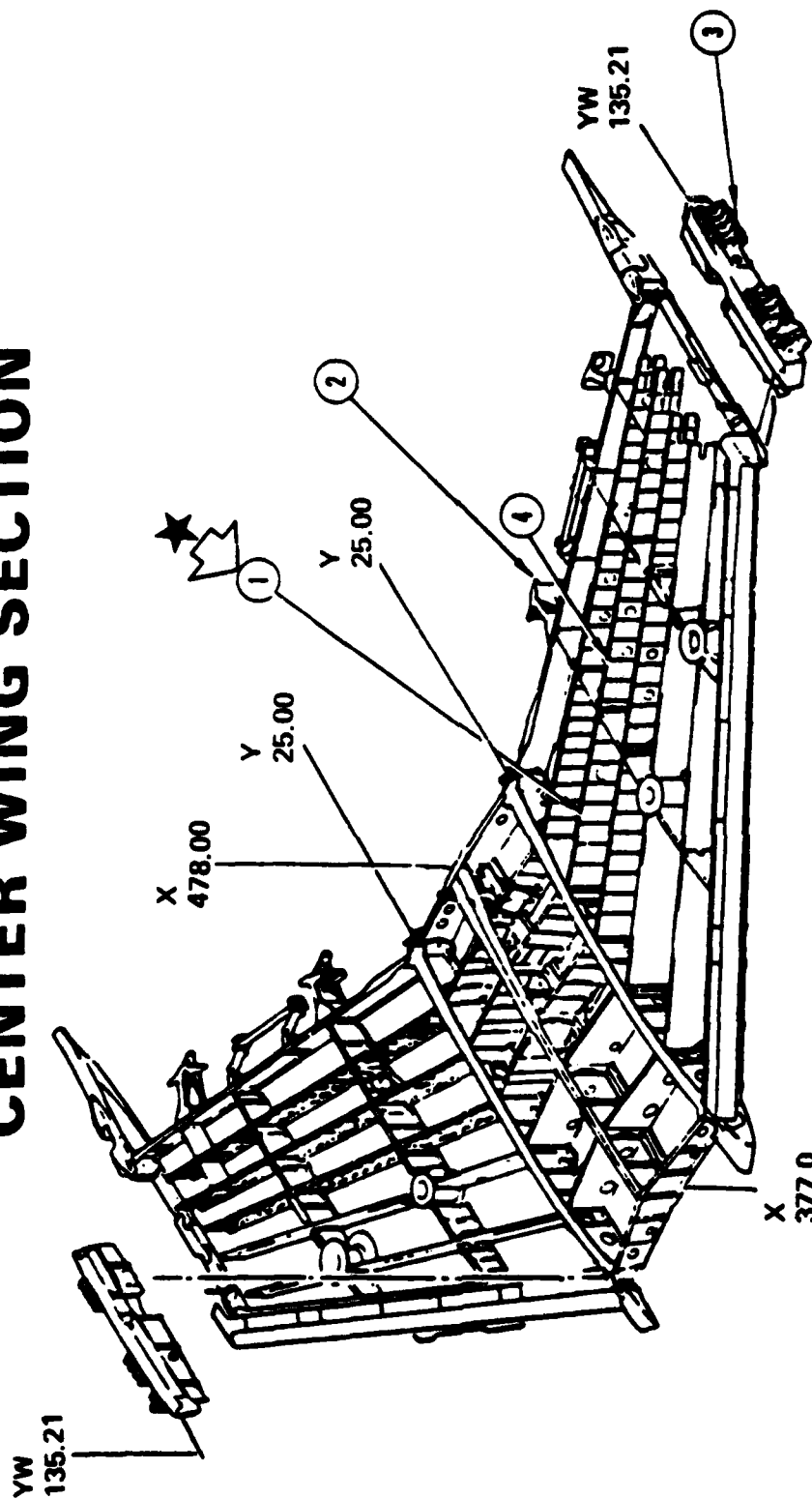


FM ANALYTICAL POINTS:

- ① LONGERON AT FS 480
- ② WING ATTACH LUGS
- ③ HORIZONTAL TAIL
- ④ VERTICAL TAIL

FIGURE B-1: LOCATION OF FUSELAGE ANALYSIS POINTS

CENTER WING SECTION



FM ANALYTICAL POINTS:

- ① WS 32
- ② WS 53
- ③ OWP LUGS
- ④ STUB HOLE

FIGURE B-2: LOCATION OF WING ANALYSIS POINTS

TABLE B.1
SPECTRA VARIATIONS USED IN ANALYSIS

- (1) $W = 1.075W$ (one standard deviation of A-7D Weight)
- (2) $W = 1.15W$
- (3) $MN = 1.15MN$ (one standard deviation of A-7D Mach Number)
- (4) $ALT = 1.15 ALT$ (one third of a standard deviation of A-7D Altitudes)
- (5) $N_Z = 1.15 N_Z$
- (6) $N_Z \leq 6.5g$
- (7) 30-30-30 mix (the baseline spectrum was a 30% general, 50% air to ground, and 20% air to air mix)
- (8) 10-50-40 mix
- (9) 50-50-0 mix

TABLE B.2

EQUATIONS USED TO DETERMINE STRESS AT THE EIGHT LOCATIONS

$$\begin{aligned}
\sigma_{WS32.2} &= 13590 - 0.84291 (W) + 0.000013661 (W)^2 + N_Z [-9164 (MN) + 0.286 (W) + \\
&\quad 7200. (MN)^2 - 0.00000227 (W)^2 + 0.000000173 (H)^2 - .052 (W1) - \\
&\quad 0.27137(W2) - 0.1298 (W3) - 0.11 (FW)] \\
\sigma_{WS53.7} &= -32419 (MN) - 0.214 (W) - 0.4 (W1) (N_Z) - 0.13 (W2) (N_Z) + 24003 (MN)^2 \\
&\quad + 0.0000035 (W)^2 - 4534 (MN) (N_Z) + 0.181 (W) (N_Z) + 3538 (MN)^2 (N_Z) \\
&\quad - 0.000001 (W)^2 (N_Z) + 286 (N_Z) - 0.02 (FW) (N_Z) + 13671 \\
\sigma_{VT} &= 0.0096 (W) (N_Y) + 0.587 (W) (\dot{P}) - 10223 (\dot{P}) - 1225 (\dot{R}) + 93 \\
\sigma_{OWP} &= -34975 (MN) - 0.542 (W) + 24378 (MN)^2 + 0.0000091 (W)^2 - 5615 (MN) \\
&\quad (N_Z) + 0.0073 (H) (N_Z) + 0.23 (W) (N_Z) + 4375 (MN)^2 (N_Z) - 0.00000158 \\
&\quad (W)^2 (N_Z) + 20855 \\
\sigma_{STUB} &= -0.034 (H) - 0.56 (W) - 0.437 (W1) (N_Z) - 0.146 (W2) (N_Z) + 0.0000086 \\
&\quad (W)^2 - 7202 (MN) (N_Z) + 0.226 (W) (N_Z) + 5800 (MN)^2 (N_Z) + 0.000000334 \\
&\quad (H)^2 (N_Z) - 0.00000162 (W)^2 (N_Z) - 0.049 (FW) (N_Z) + 10376 \\
\sigma_{HT} &= 6833 (N_Z) (MN) + 7091 (\dot{Q}) - 2346 (N_Z) - 0.139 (N_Z) (W2) - 0.446 (W1) + \\
&\quad 0.35 (N_Z) (FW) - 0.06 (W) (N_Z) + 0.335 (N_Z) (W3) - 0.626 (FW) + \\
&\quad 3396 (MN)^2 + 724 \\
\sigma_{LUG} &= 1503 (N_Z) (MN) + 1443 (\dot{R}) - 0.136 (N_Z) (W2) + 0.05 (N_Z) (W) - 0.264 \\
&\quad (N_Z) (W1) + 49064 (MN)^2 - 791 (\dot{P}) - 69841 (MN) + 354 (\dot{Q}) - 496 (N_Z) + \\
&\quad 23922 \\
\sigma_{LONG} &= 3076 (N_Z) (MN) + 1608 (\dot{R}) - 0.1457 (N_Z) (W2) + 1085 (\dot{Q}) - 0.226 \\
&\quad (N_Z) (W1) + 57658 (MN)^2 - 82139 (MN) + 0.634 (W) (Q) - 864 (N_Z) - \\
&\quad 396 (\dot{P}) + 29252
\end{aligned}$$

Where:

W = Airplane gross weight
 W1 = Store Station 1 weight
 W2 = Store Station 2 weight
 W3 = Store Station 3 weight
 FW = Wing fuel weight
 N_Z = Vertical load factor
 N_Y = Lateral load factor

MN = Mach number
 H = Altitude
 \dot{P} = Roll acceleration
 \dot{Q} = Pitch rate
 \ddot{Q} = Pitch acceleration
 \dot{R} = Yaw acceleration

CRACK GROWTH AT WING STATION 32

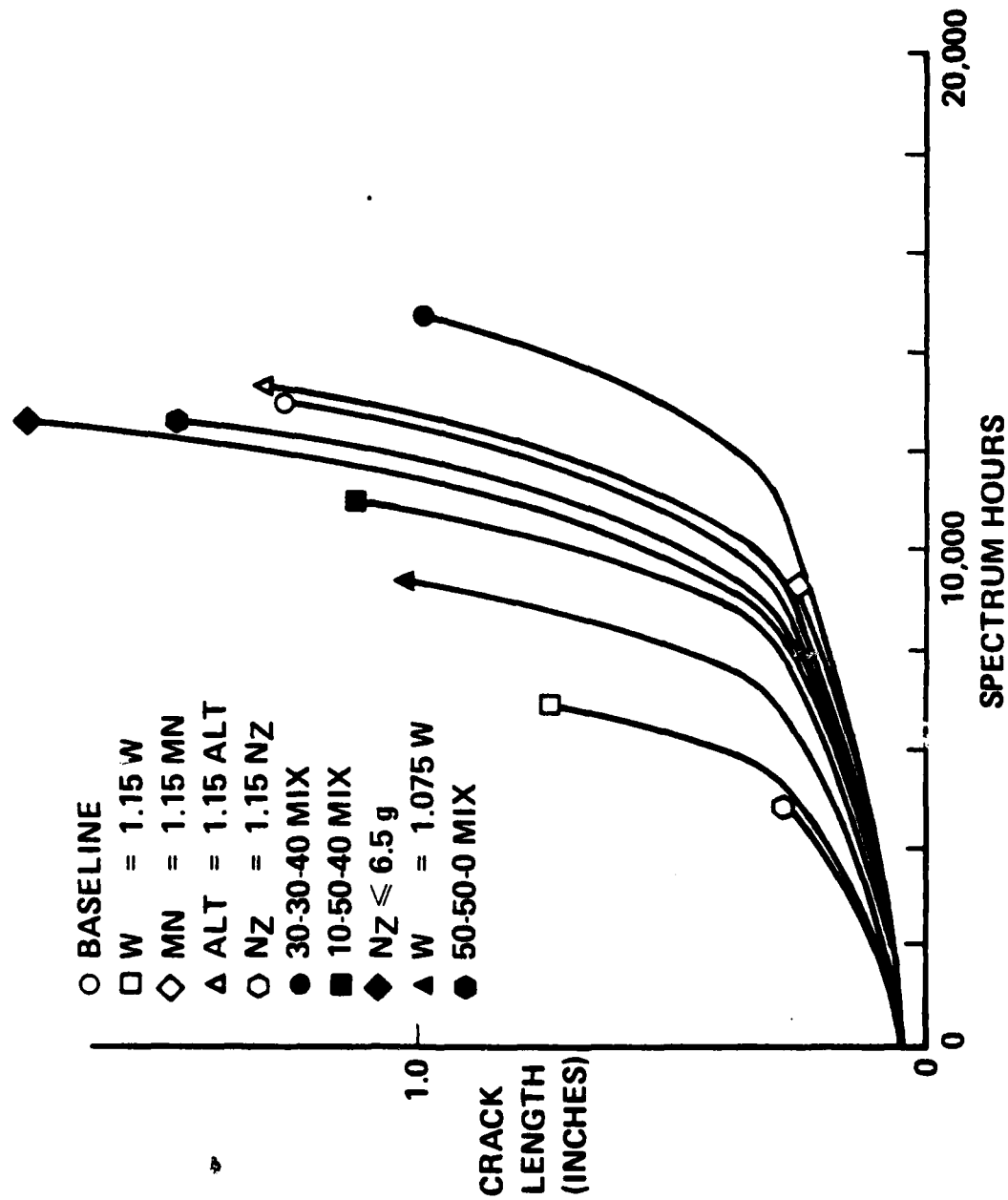


FIGURE B-3: CRACK GROWTH AT WS 32

CRACK GROWTH AT WING STATION 53

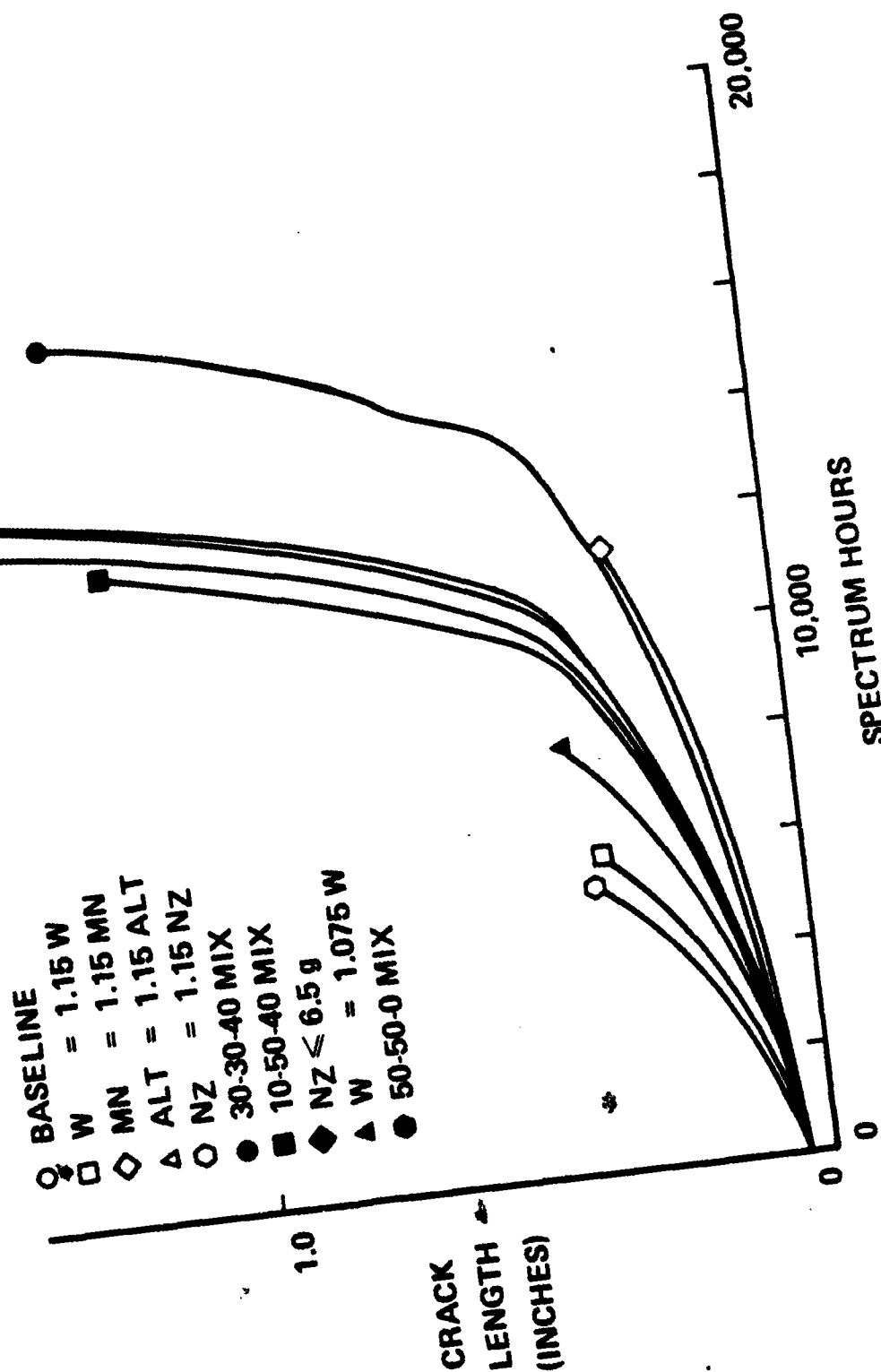


FIGURE B-4: CRACK GROWTH AT WS 53

CRACK GROWTH AT WING INBOARD AFT PYLON STUB HOLE

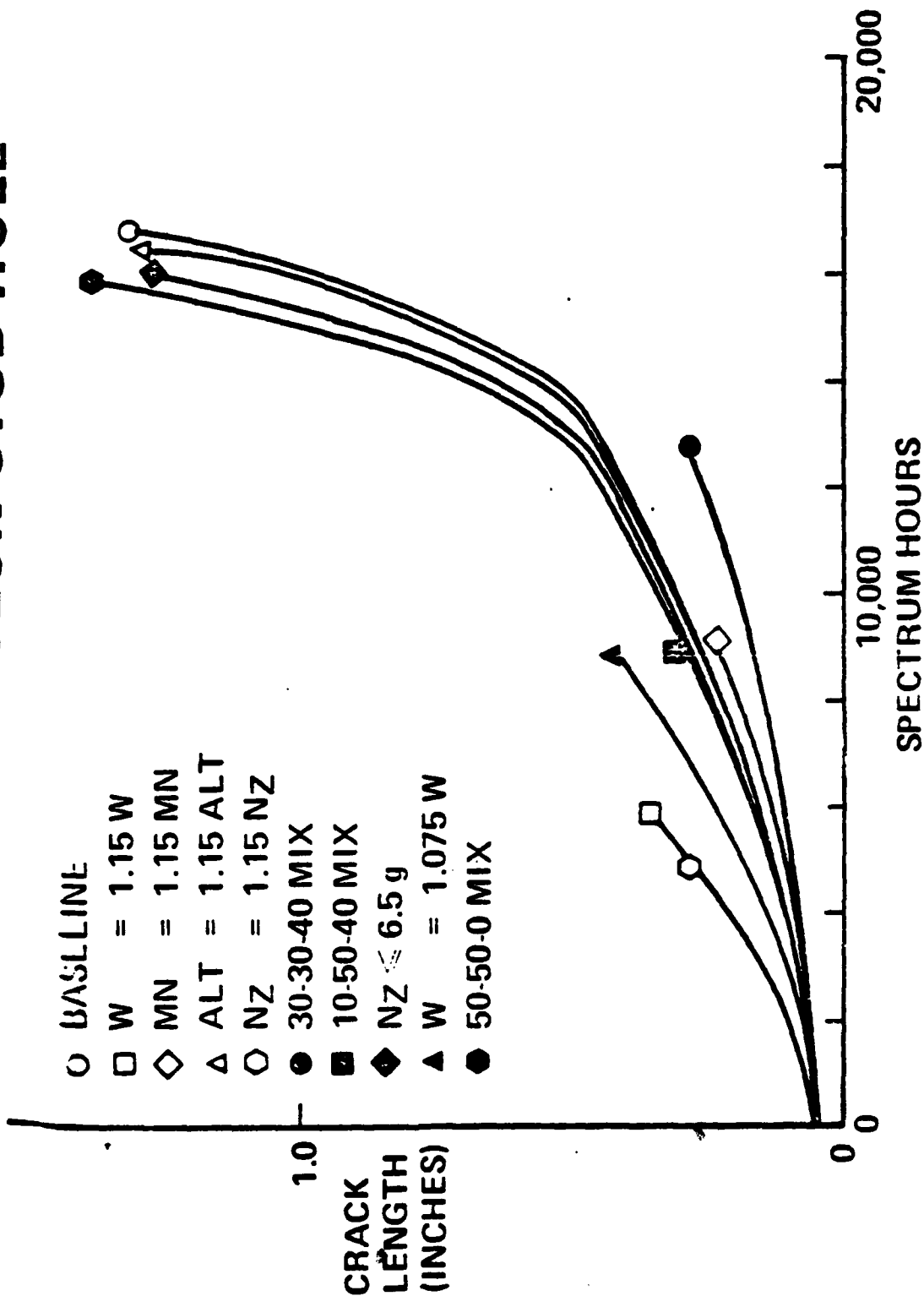


FIGURE B-5: CRACK GROWTH AT PYLON STUB HOLE

CRACK GROWTH AT OUTER WING PANEL LUG

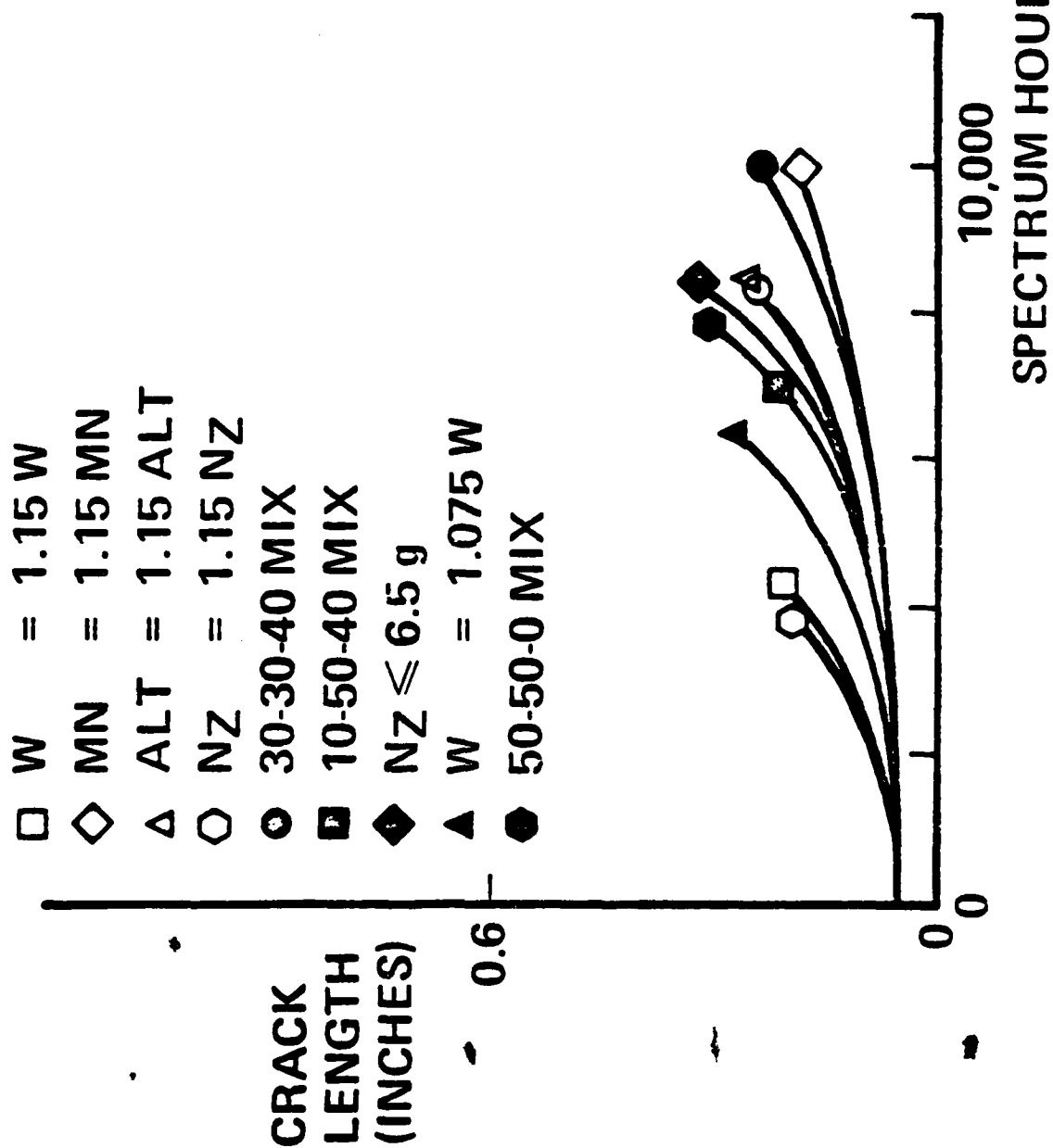


FIGURE B-6: CRACK GROWTH AT OUTER PANEL LUG

CRACK GROWTH AT LONGERON AND WA LUG

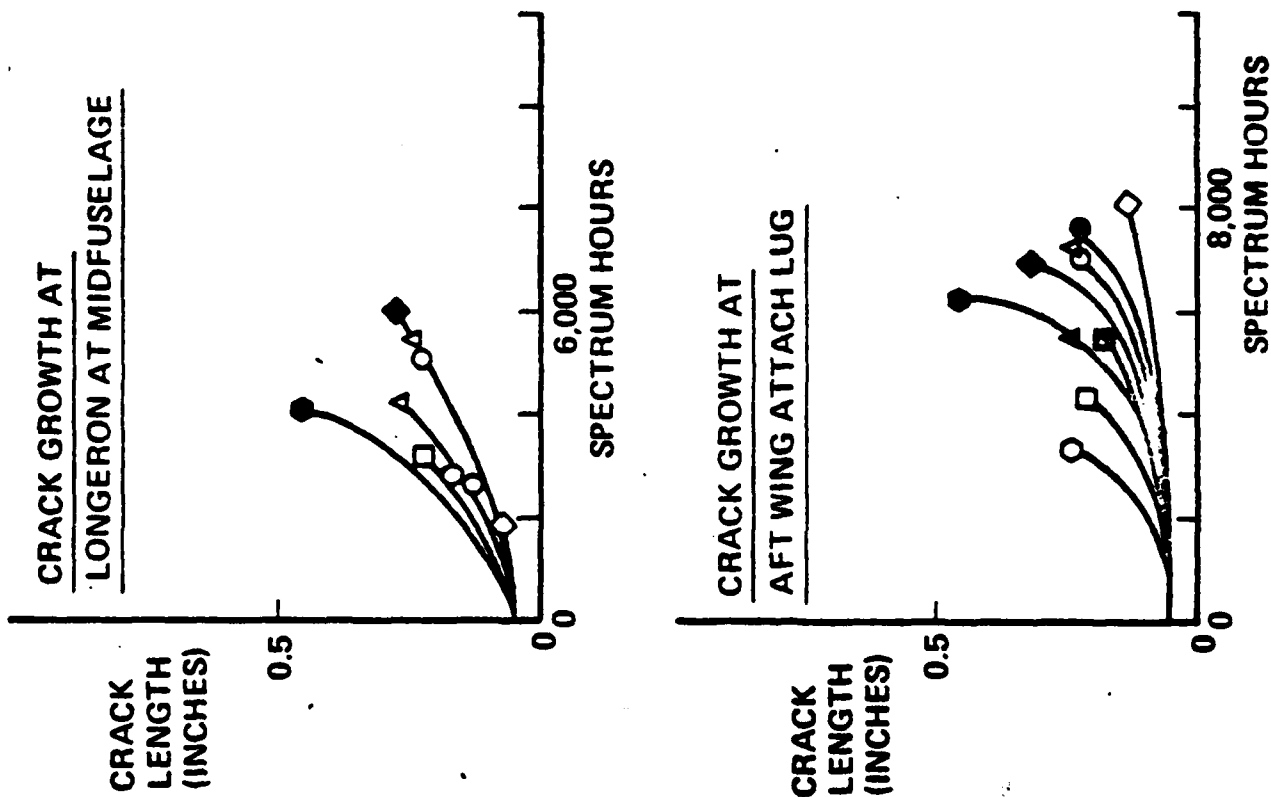


FIGURE B-7: CRACK GROWTH AT LONGERON AND WA LUG

CRACK GROWTH AT HORIZONTAL TAIL

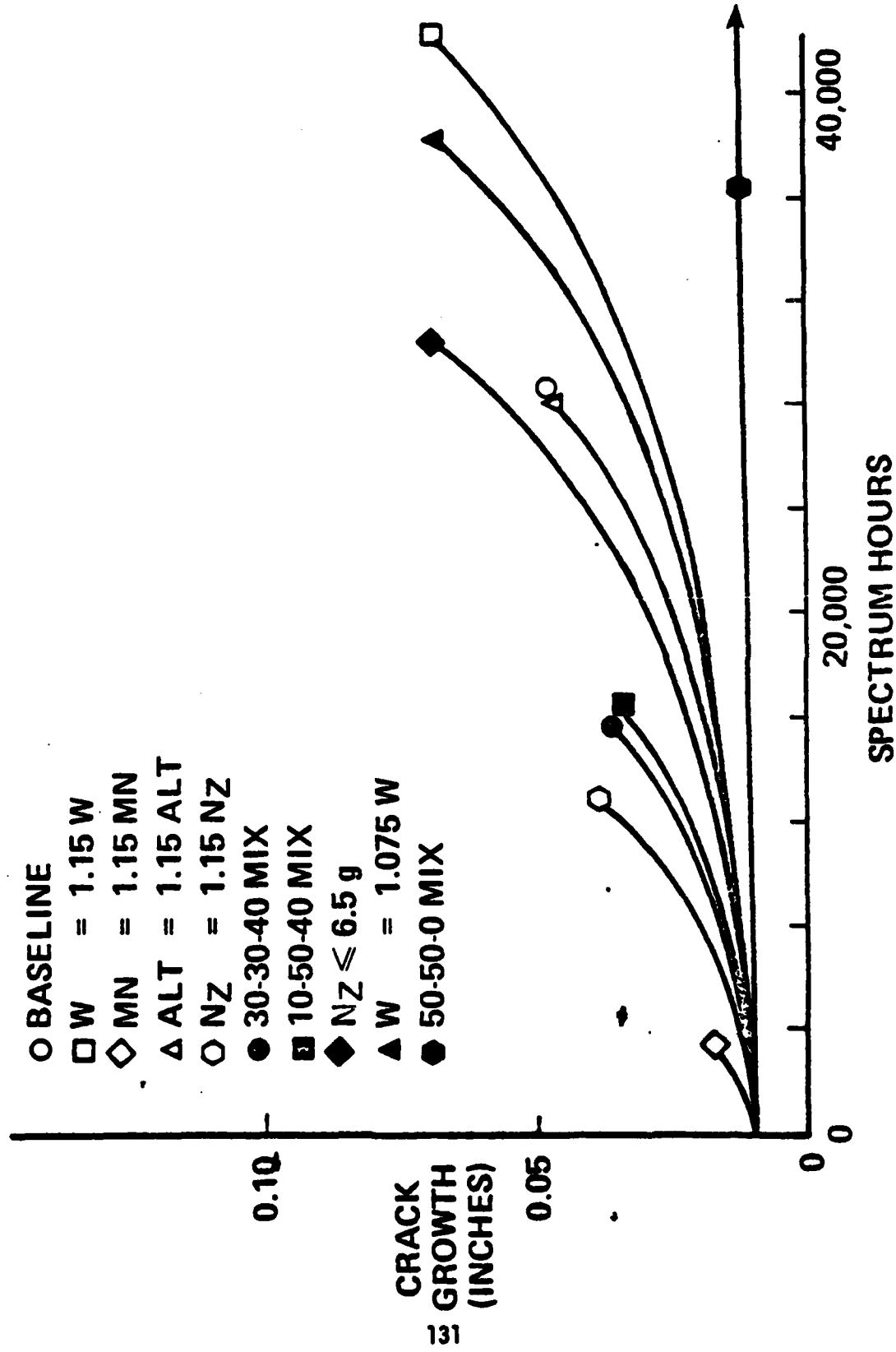
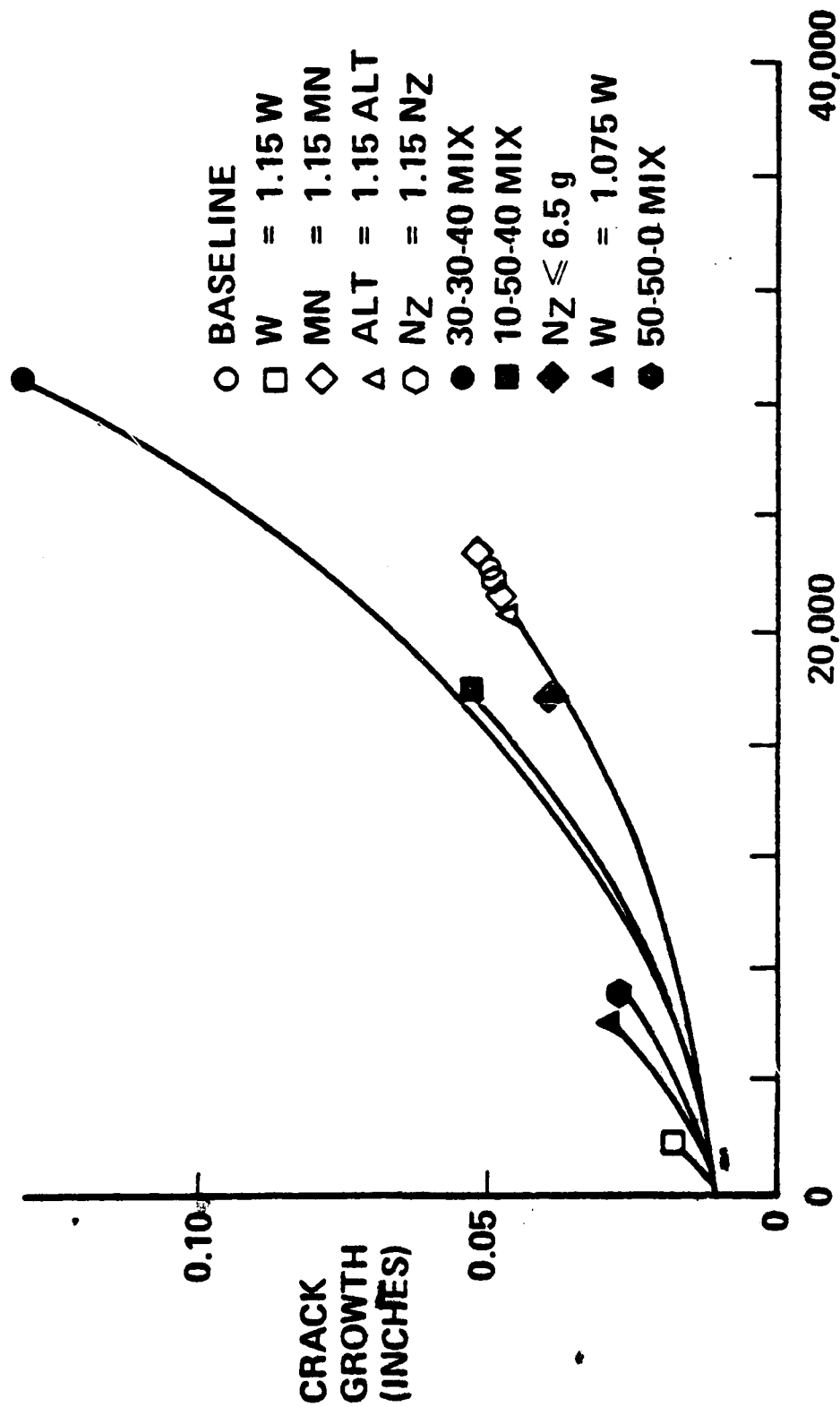


FIGURE B-8: CRACK GROWTH AT HORIZONTAL TAIL

CRACK GROWTH AT VERTICAL TAIL



SPECTRUM HOURS

FIGURE B -9: CRACK GROWTH AT VERTICAL TAIL

TABLE B.3

SPECTRUM VARIATION EFFECTS

LOCATION	BASE LINE	1.075		1.15		1.15		1.15		1.15		NZ < 6.5		30-30-40		10-50-50		50-50-0	
		W	W	W	MN	ALT	NZ	NZ	NZ	NZ	NZ	NZ	40	50	50	0			
WS 32	1.0	0.72	0.53	0.72	1.02	0.38	0.97	1.13	0.92	0.96									
WS 53	1.0	0.59	0.44	0.85	1.00	0.40	1.00	1.23	0.88	0.95									
VERTICAL TAIL	1.0	0.27	0.08	1.00	1.00	1.00	1.00	1.30	0.80	0.32									
OWP FOLD LUG	1.0	0.76	0.52	1.19	1.00	0.47	1.00	1.20	0.84	0.94									
STUB HOLD	1.0	0.54	0.36	0.54	0.99	0.30	0.96	0.77	0.54	0.95									
HORIZONTAL TAIL	1.0	1.33	1.47	0.12	1.00	0.45	1.07	0.55	0.57	9.00									
WING ATTACH LUG	1.0	0.77	0.61	1.13	1.00	0.47	0.97	1.07	0.77	0.89									
LONGERON	1.0	0.80	0.61	0.35	1.00	0.55	1.16	0.51	0.49	0.78									

NORMALIZED RATE OF CRACK GROWTH AT WS 53 AND STUB HOLE RELATIVE TO REFERENCE

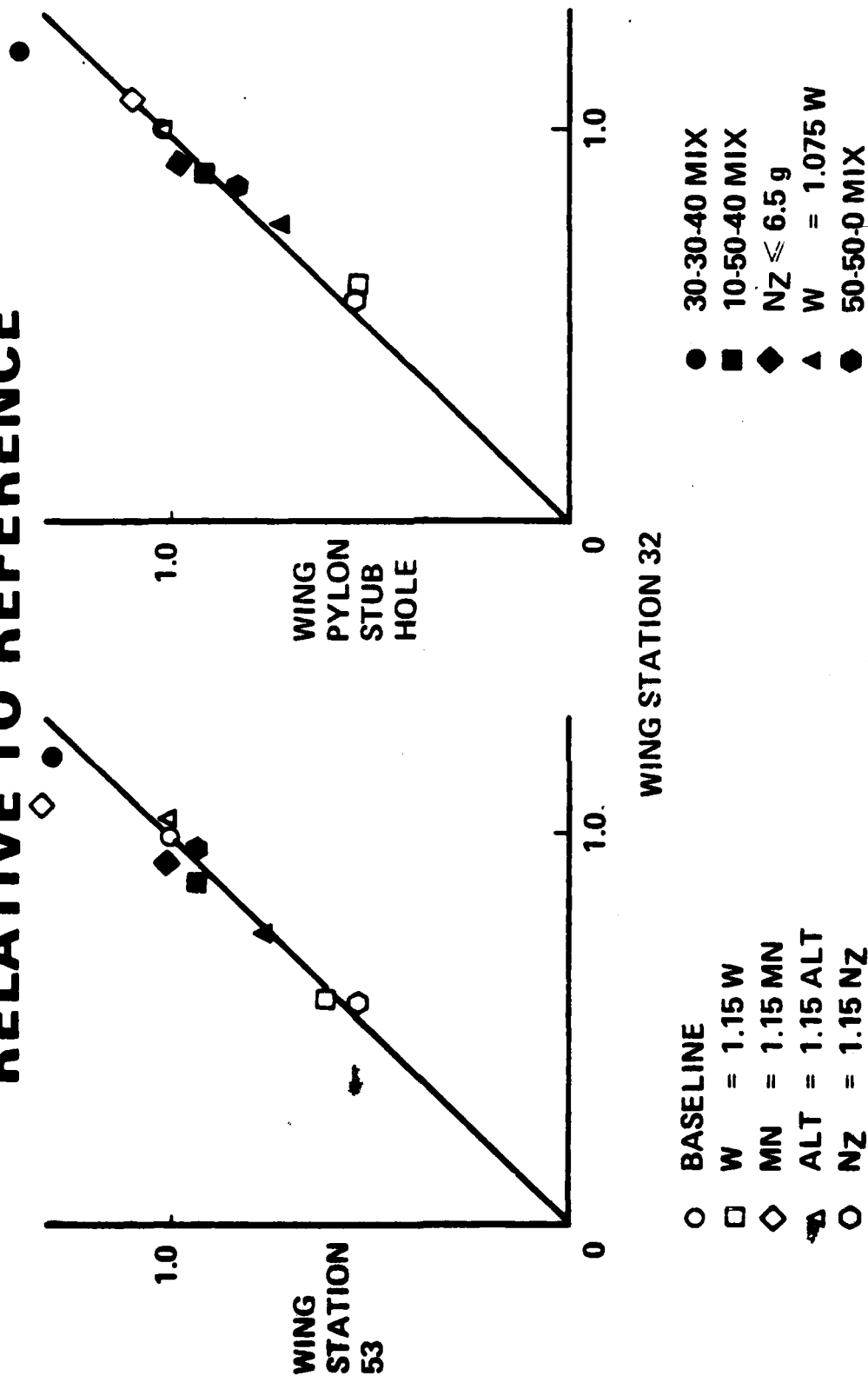


FIGURE B-10: NORMALIZED RATE OF CRACK GROWTH AT WS 53 AND PYLON STUB HOLE

NORMALIZED RATE OF CRACK GROWTH AT OWP AND WING ATTACH LUGS RELATIVE TO REFERENCE

- | | |
|------------------|-------------------|
| ○ BASELINE | ● 30-30-40 MIX |
| □ W = 1.15 W | ■ 10-50-40 MIX |
| ◇ MN = 1.15 MN | ◆ NZ ≤ 6.5 g |
| △ ALT = 1.15 ALT | ▲ W = 1.075 W |
| ○ NZ = 1.15 NZ | ● 50-50-0 MIX |

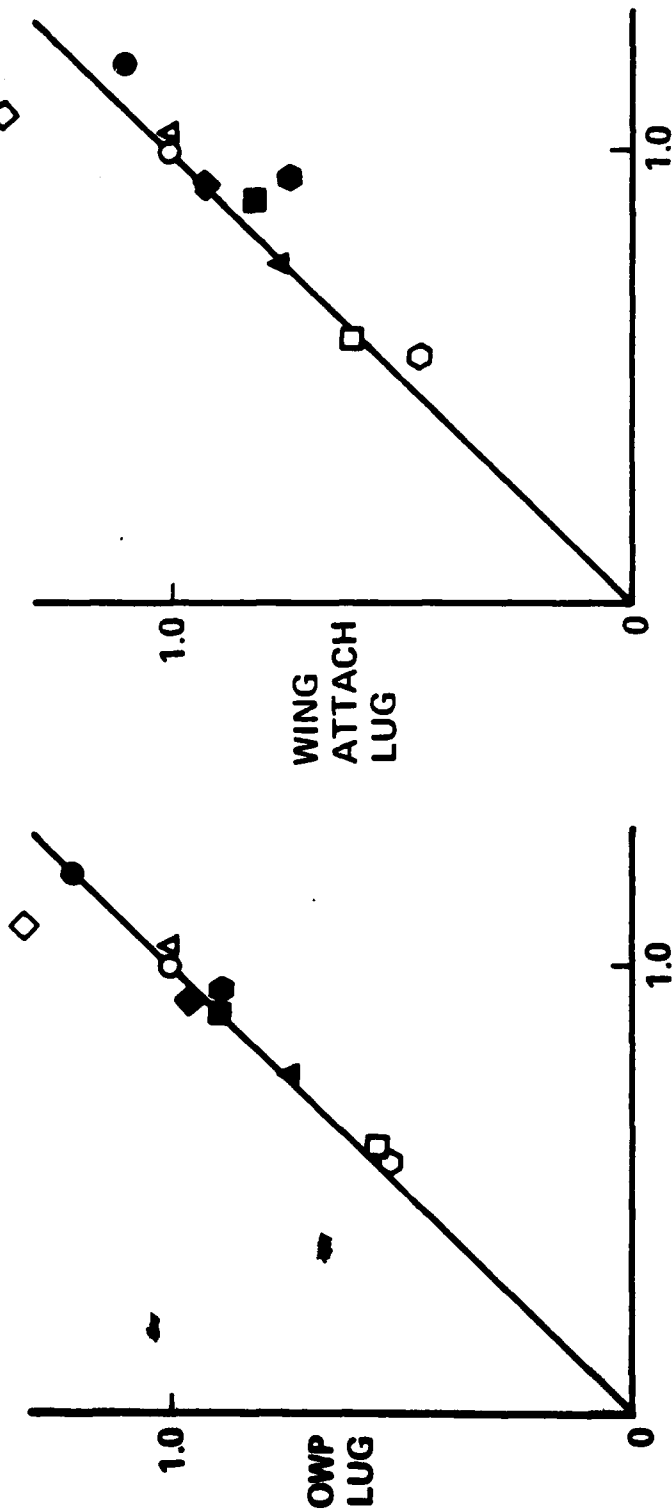
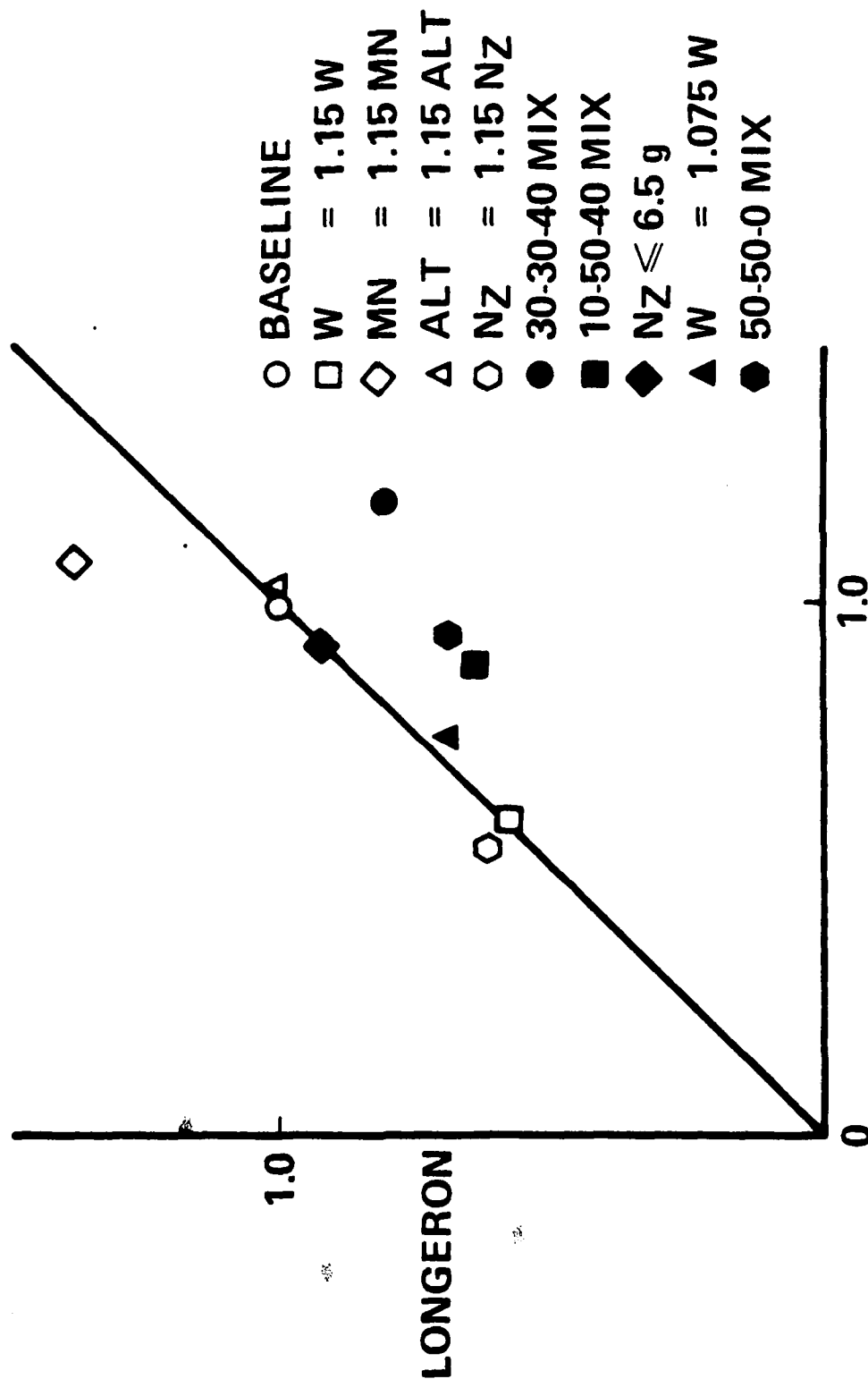


FIGURE B-11: NORMALIZED RATE OF CRACK GROWTH
AT OWP AND WA LUGS

NORMALIZED RATE OF CRACK GROWTH AT LONGERON RELATIVE TO REFERENCE



WING STATION 32

FIGURE B-12: NORMALIZED RATE OF CRACK GROWTH AT LONGERON

NORMALIZED RATE OF CRACK GROWTH AT HORIZONTAL TAIL AND VERTICAL TAIL RELATIVE TO REFERENCE

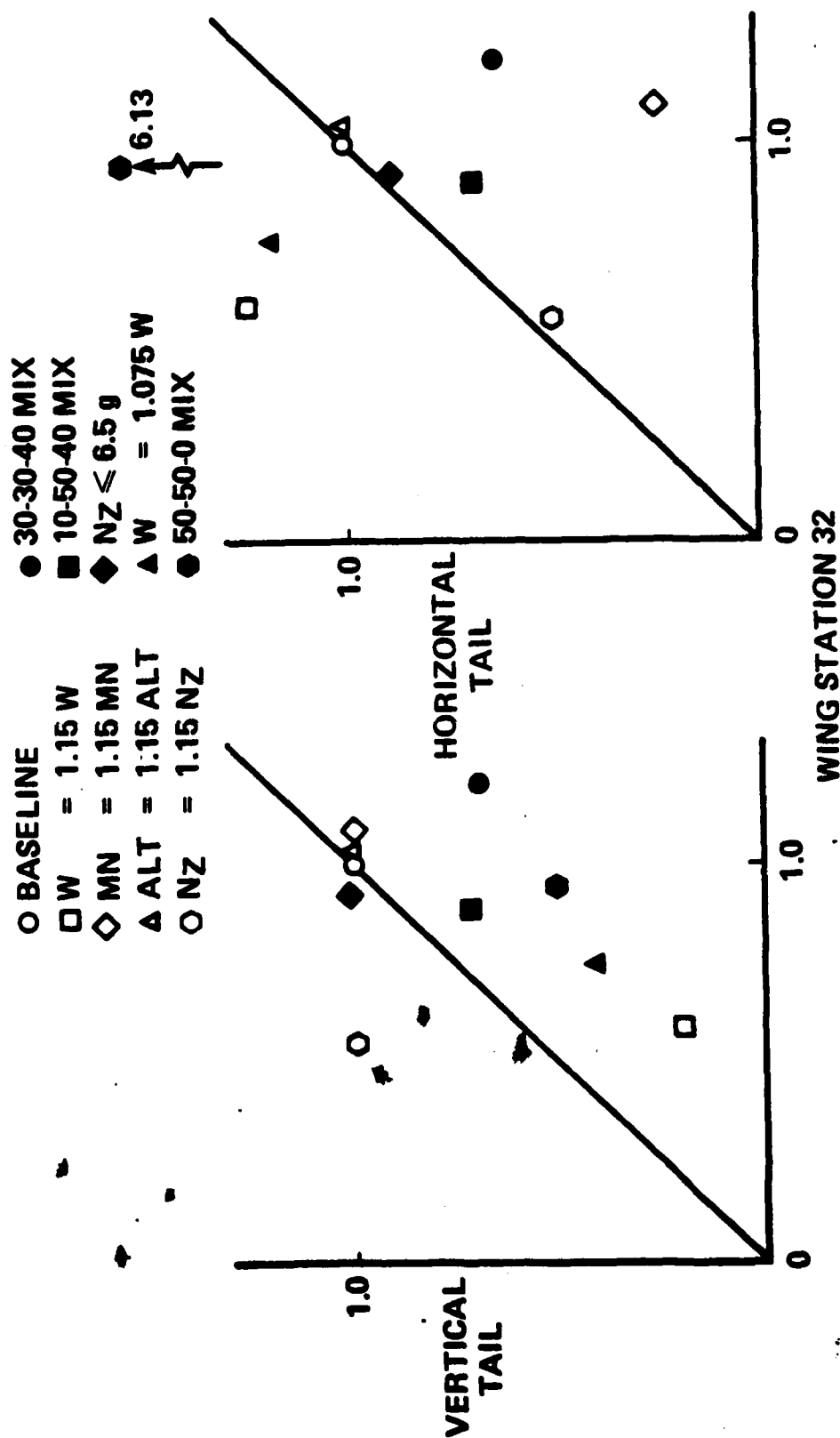


FIGURE B-13: NORMALIZED RATE OF CRACK GROWTH
AT VERTICAL AND HORIZONTAL TAILS

APPENDIX C

A-7D MSR PROGRAM SUMMARY

The purpose of this program was to develop an installation design for the MSR and to demonstrate its feasibility as an effective device for evaluating the n_2 -to-stress relationship for the A-7D airplane. In this sense, the program has benefit both to the A-7D IAT and L/ESS functions. Detailed information is available in Reference 11.

The program realized MSR strain data from two Air Force A-7D airplanes for a total of 150 flight hours. The airplanes also had the standard counting accelerometer installation aboard.

Figures C-1 and C-2 summarize the stress exceedance data taken from the two airplanes. This data is normalized to 1000 flight hours and is compared to like data from the flight test program (described in Reference 11) conducted during the A-7D ASIP. Figures C-3 and C-4 presents comparative counting accelerometer exceedance data in the same manner. The MSR data is seen to vary significantly in terms of stress from the counting accelerometer results. Figure C-5 presents the net variation of the results in terms of n_2 -to-stress relationships.

Table C.1 is a comparison of the effects of this variation in terms of damage index. That is, the current Air Force tracking program would predict a damage index of .201 for an airplane flying the composite (reference) spectrum. A damage model (the EFFGRO routine) would have predicted a damage index of .195, a 3% difference. The other entries in the table present similar calculations of damage indices for comparison. It is seen that the use of the counting accelerometer data (as is done in the official tracking program) provide damage indices substantially lower than like values calculated from the MSR data.

If the MSR program were to be considered a mini-L/ESS program, it would be a perfect example of how the IAT program is updated by the L/ESS. If the results of this Phase I study are validated by the follow-on program, it is clear that the A-7D damage tracking method should be updated by altering the n_a -to-stress relationship used.

As discussed in Section 7, for airplanes having localized critical areas in the wing, the MSR may constitute an effective L/ESS method.

A/P 69-6217 vs. Composite
Stress Spectra Comparison

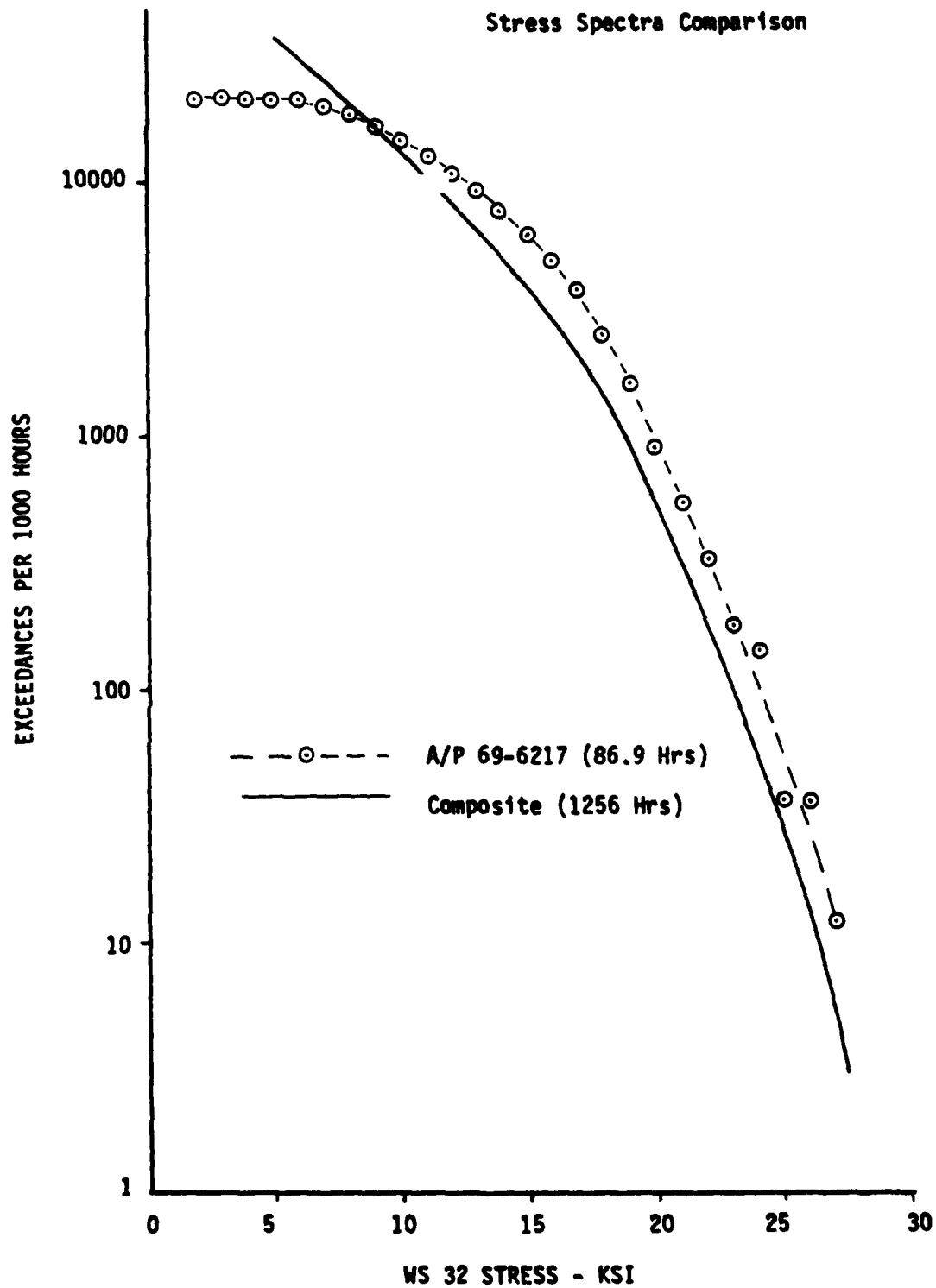


FIGURE C

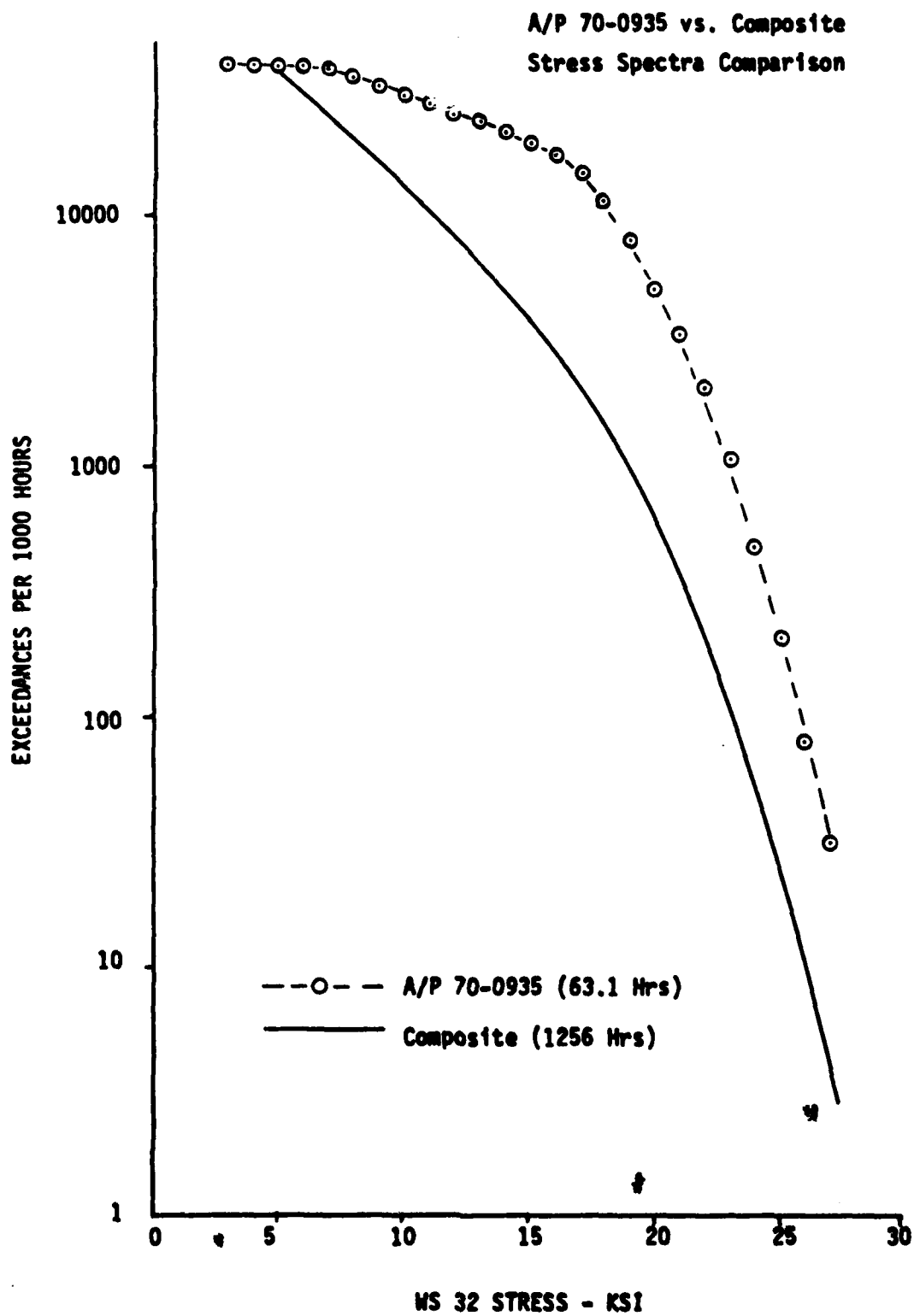


FIGURE C

A/P 69-6217 vs. Composite
 N_2 - Spectra Comparison

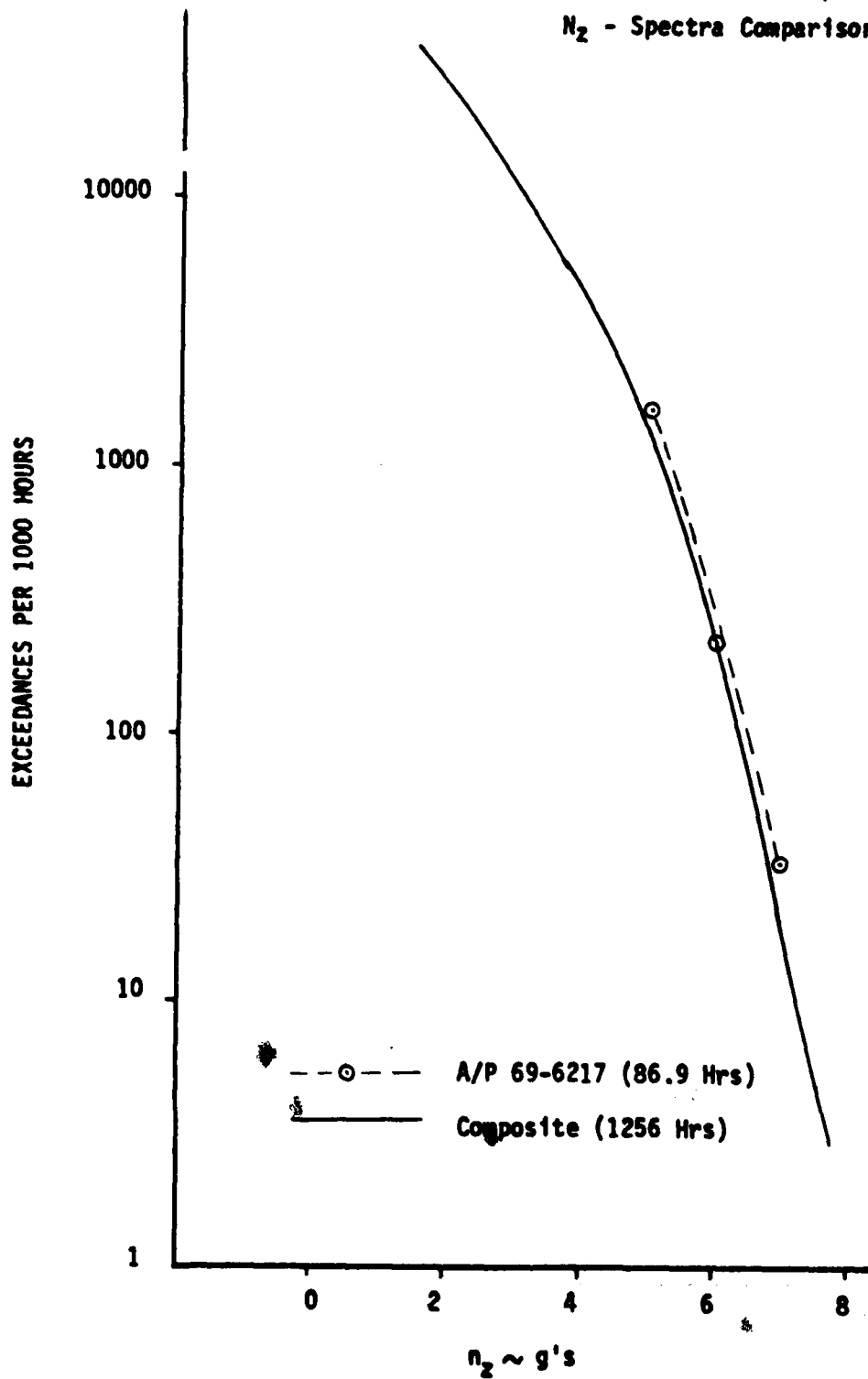


FIGURE C

A/P 70-0935 vs. Composite
N₂ Spectra Comparison

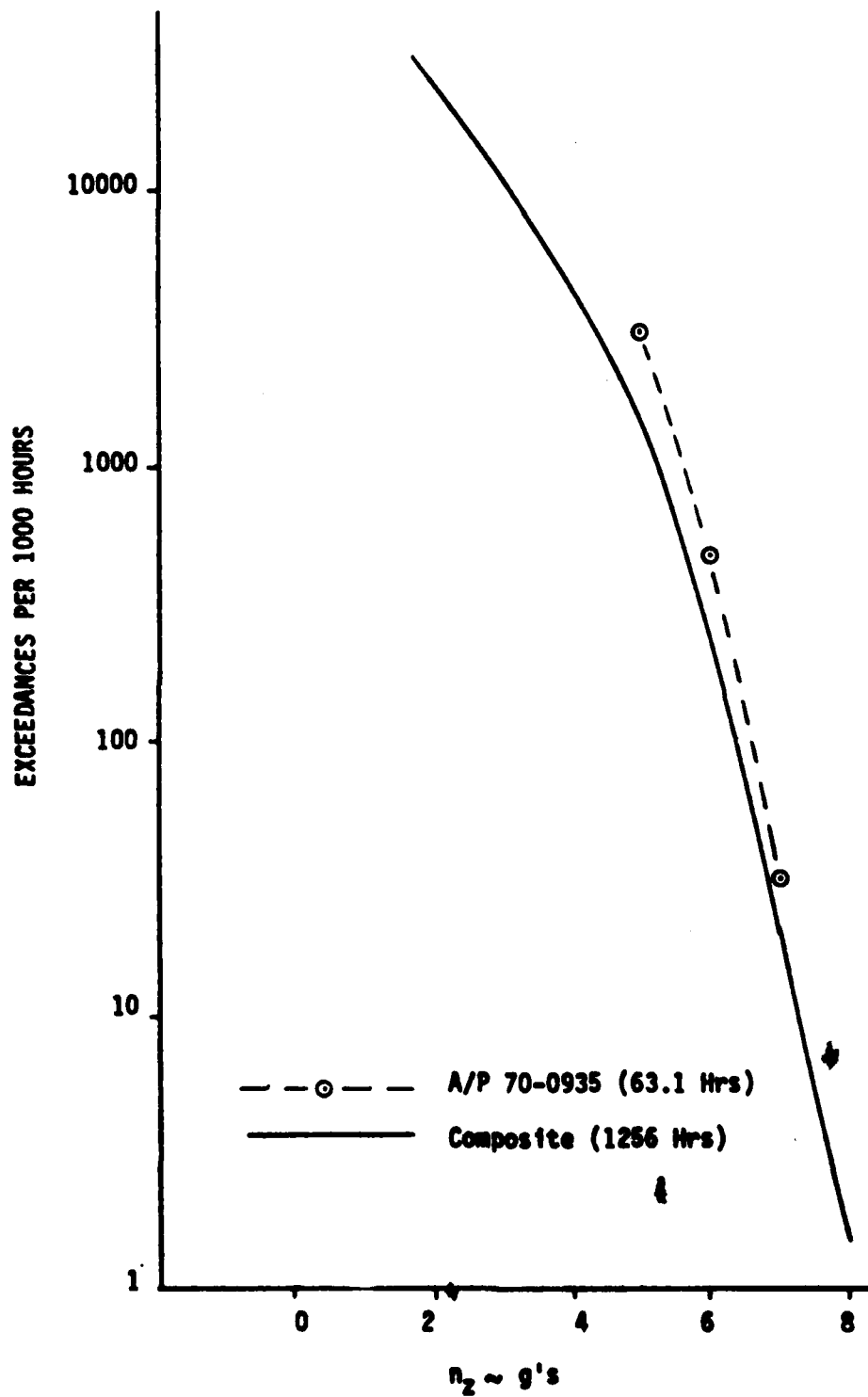


FIGURE C

A-7D N_2 - Stress Relationships

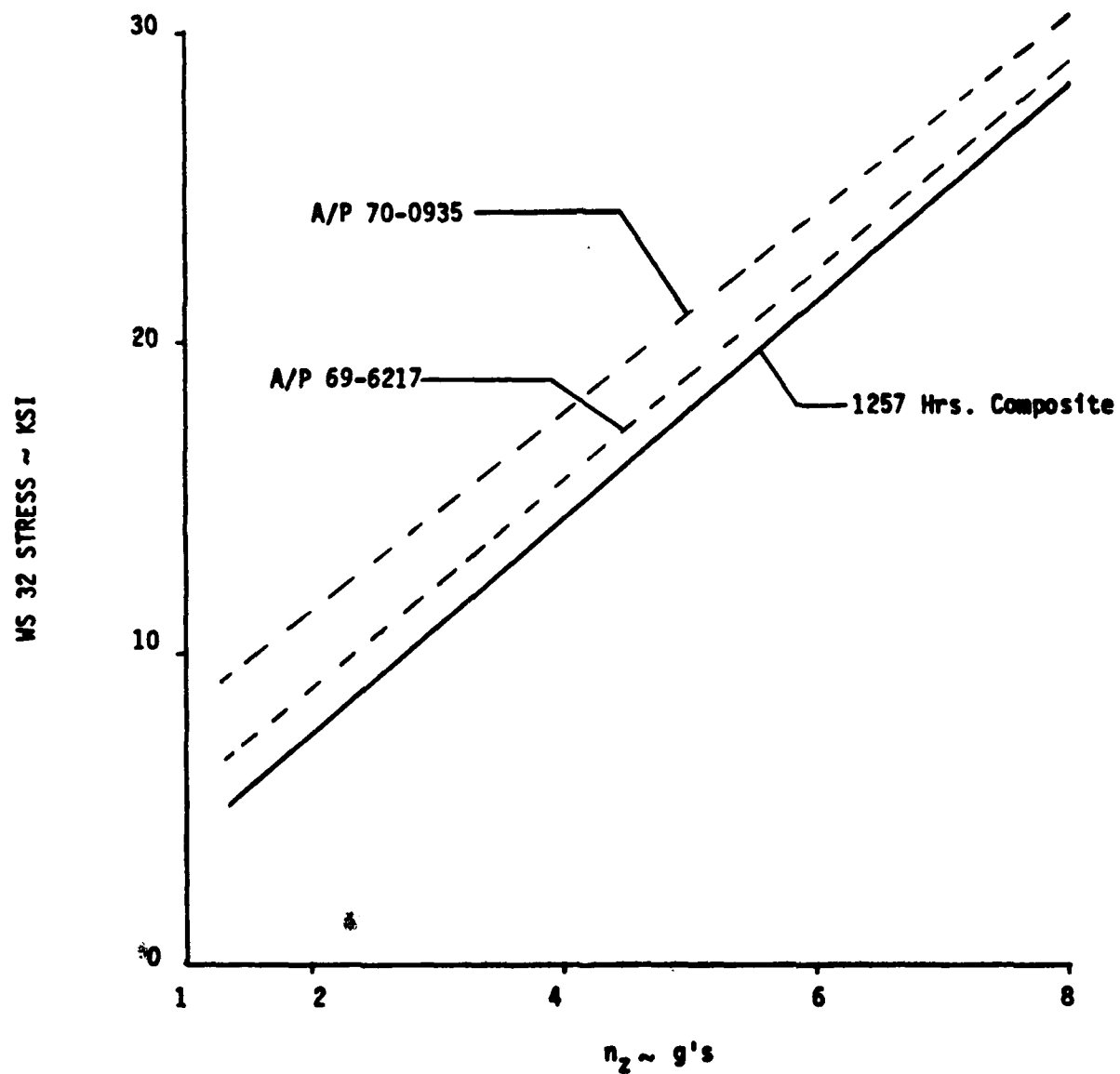


FIGURE C

TABLE C.1 DAMAGE INDEX COMPARISON

STRESS SPECTRUM	NZ EXCEEDANCES PER 1000 HRS				1000 FLIGHT HRS		PERCENT DIFFERENCE IN D.I.
	N5	N6	N7	N8	CURRENT DAMAGE TRACKING D.I.	EFFGRO D.I.	
Composite (1256 hrs)	1405.3	207.02	17.517	1.592	.201	.195	3.0
69-06217 (86.9 hrs)	1680.1	230.15	34.52	0.	.257	.347	*35.0
70-0935 (63.1 hrs)	3090.3	475.44	31.7	0.	.443	.629	*42.0

*Damage Underestimated by Current Damage Tracking

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